Heaven-Sent Neutrino Interactions From TeV to PeV

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

UCL HEP Seminar

London, December 08, 2017

UNIVERSITY OF COPENHAGEN

Two seemingly unrelated questions –

1. Where are the most energetic particles coming from?

2. What is the structure of matter at the smallest scales?

Symmetry Magazine

Heaven-Sent Neutrino Interactions From TeV to PeV

^ WITH ASTROPHYSICAL NEUTRINOS

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Neutrinos interactions are weak ...

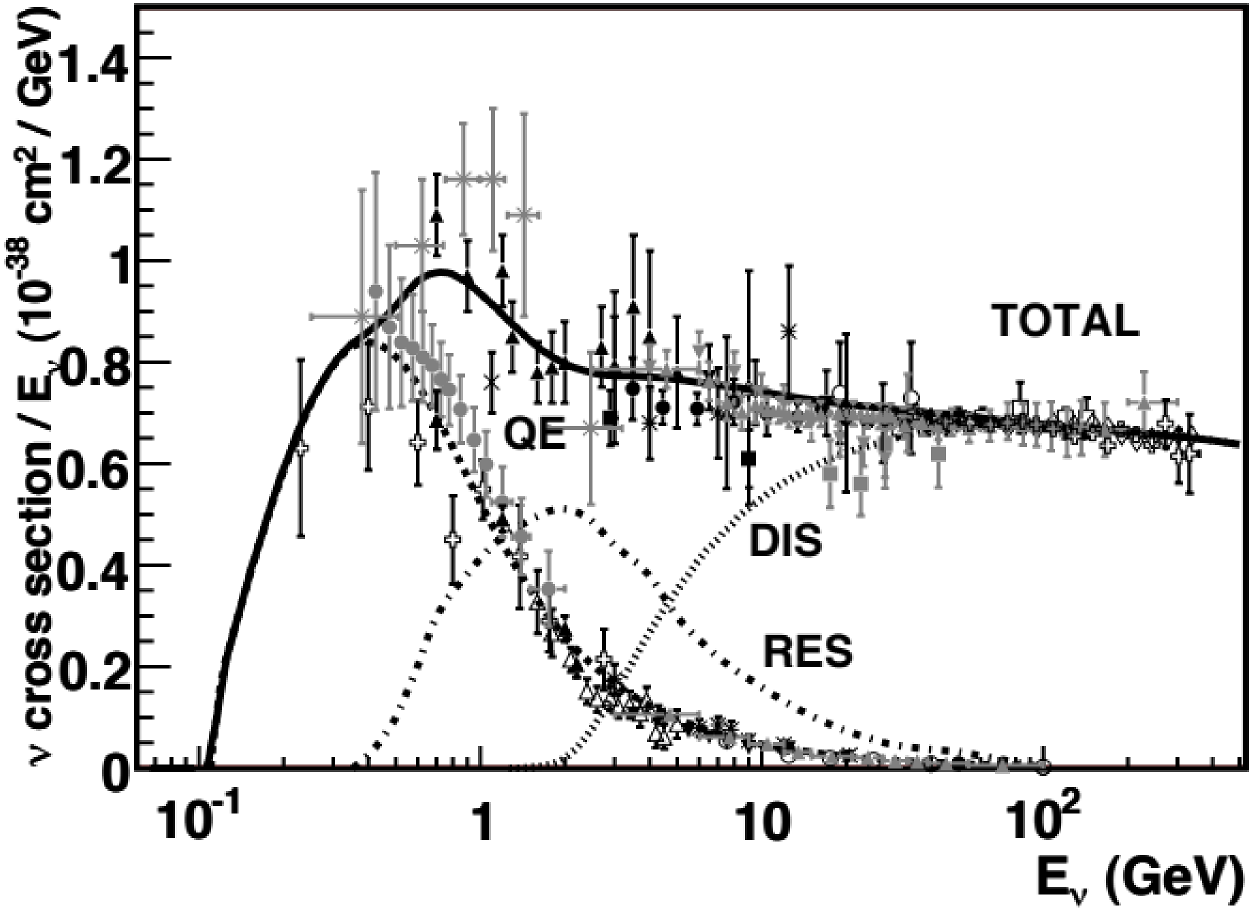
… but we *are* persistent

At center-of-mass energy of 1 GeV:

$$\sigma_{pp} \sim 10^{-28}\ \mathrm{cm}^2$$

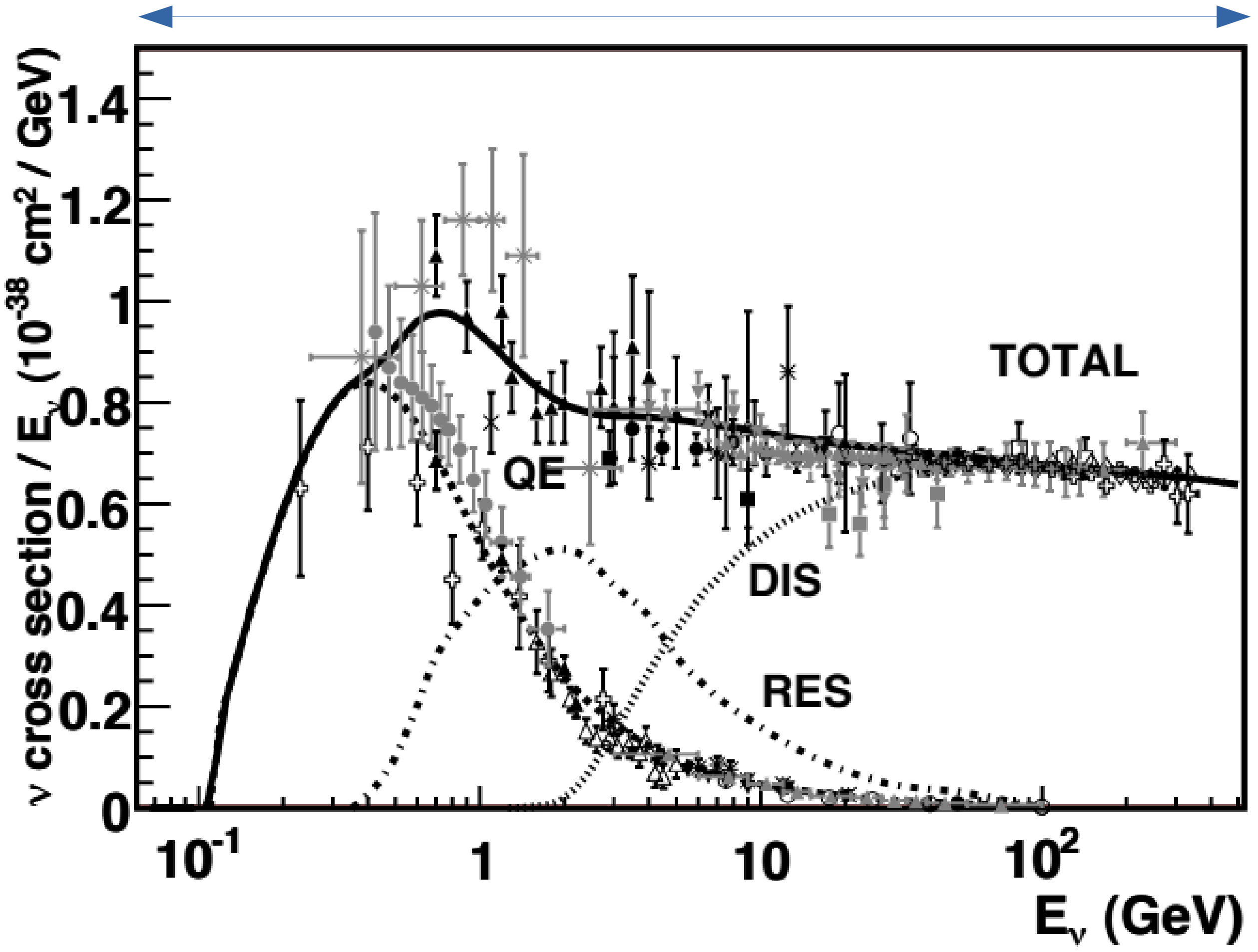
$$\sigma_{\gamma p} \sim 10^{-29}\ \mathrm{cm}^2$$

$$\sigma_{\nu p} \sim 10^{-38}\ \mathrm{cm}^2$$



Particle Data Group

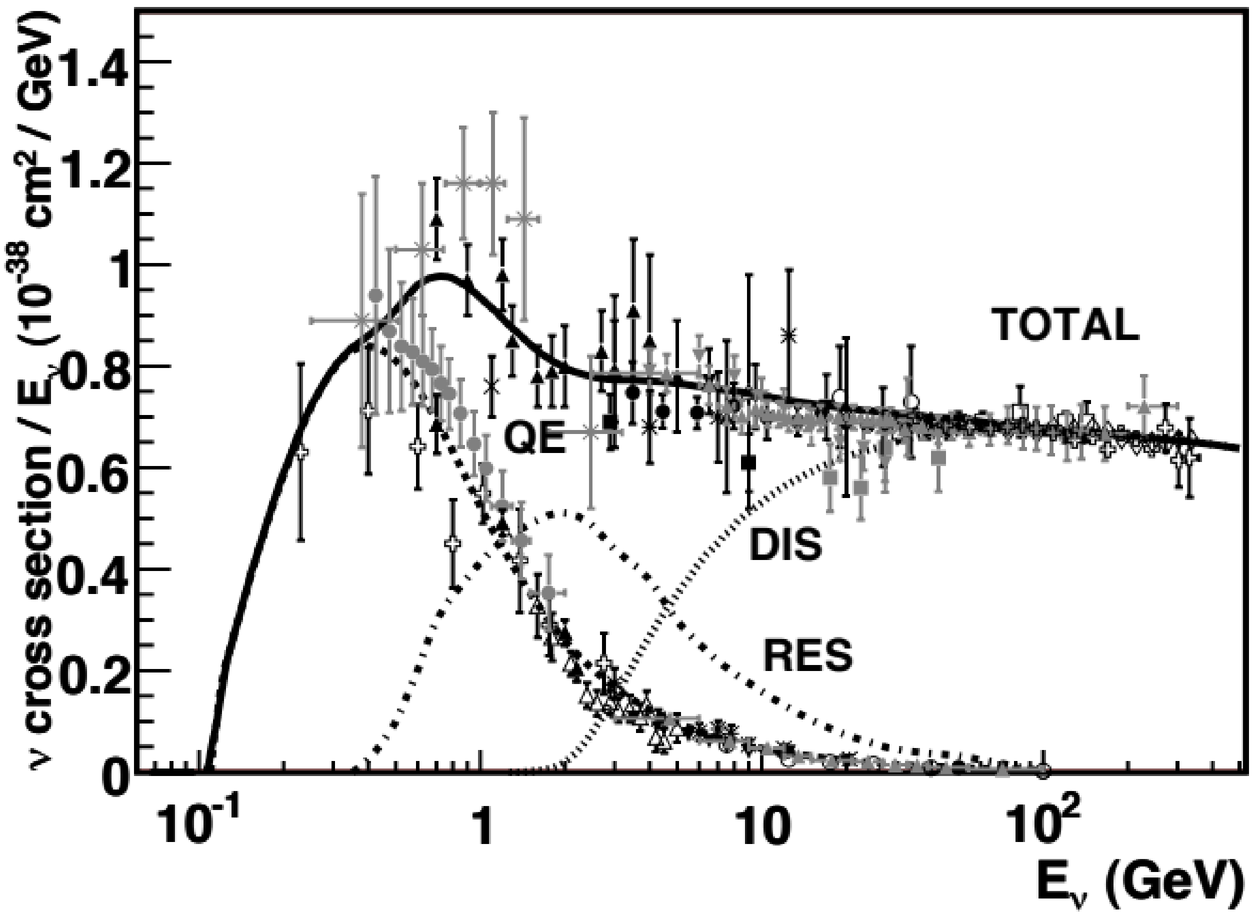
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group

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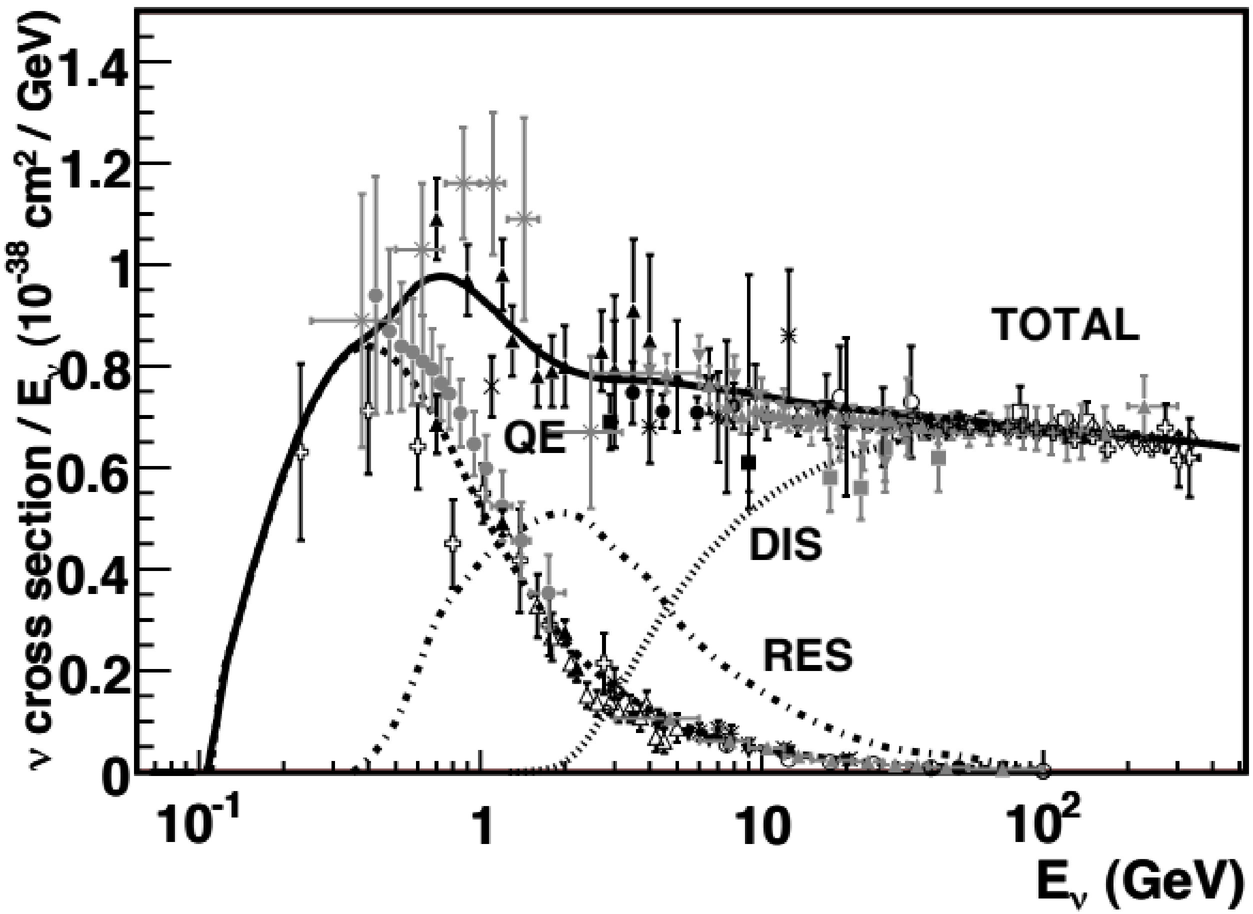
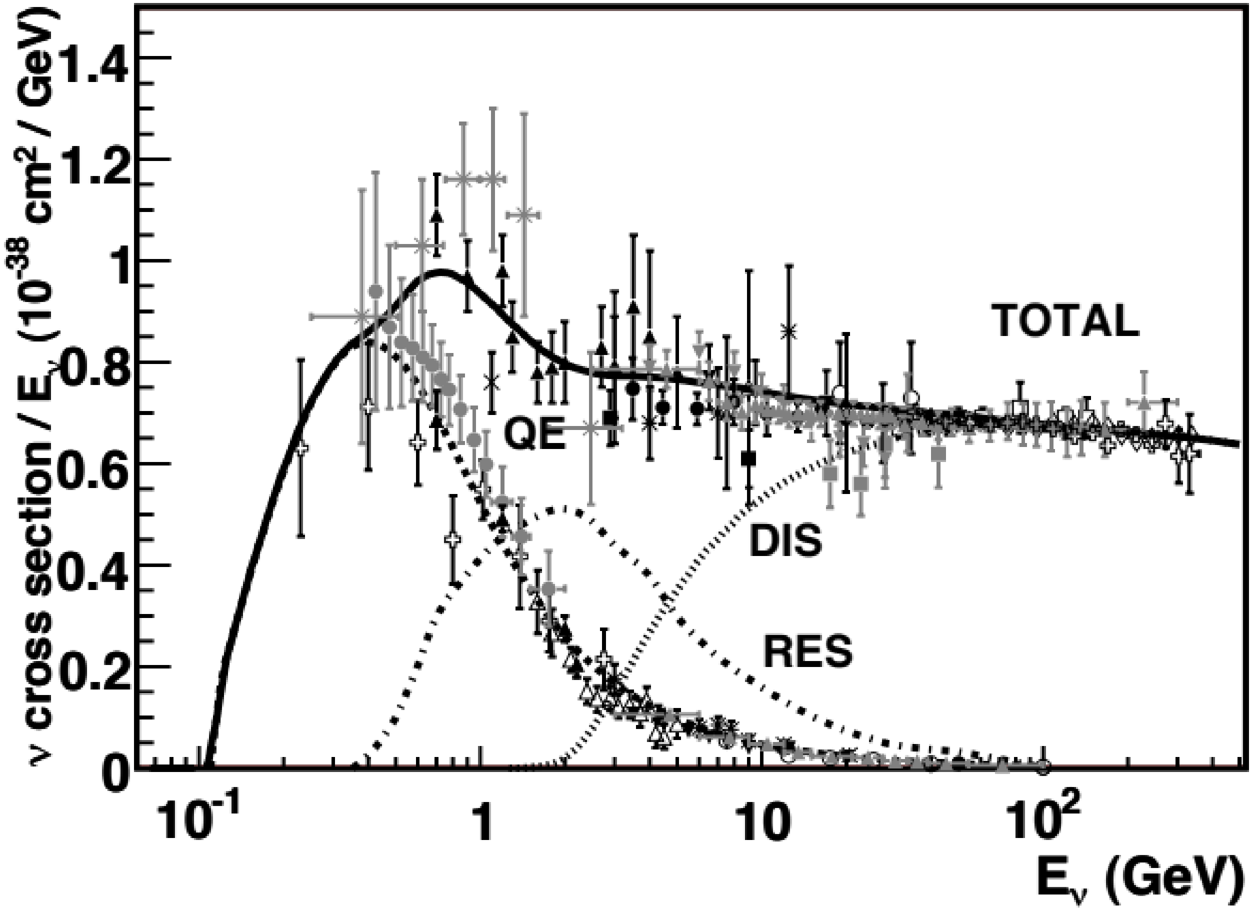


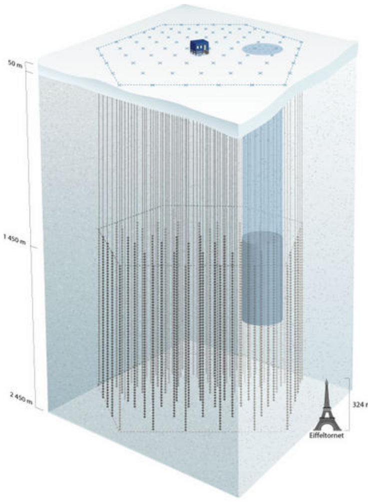
No measurements
… until now!

Particle Data Group

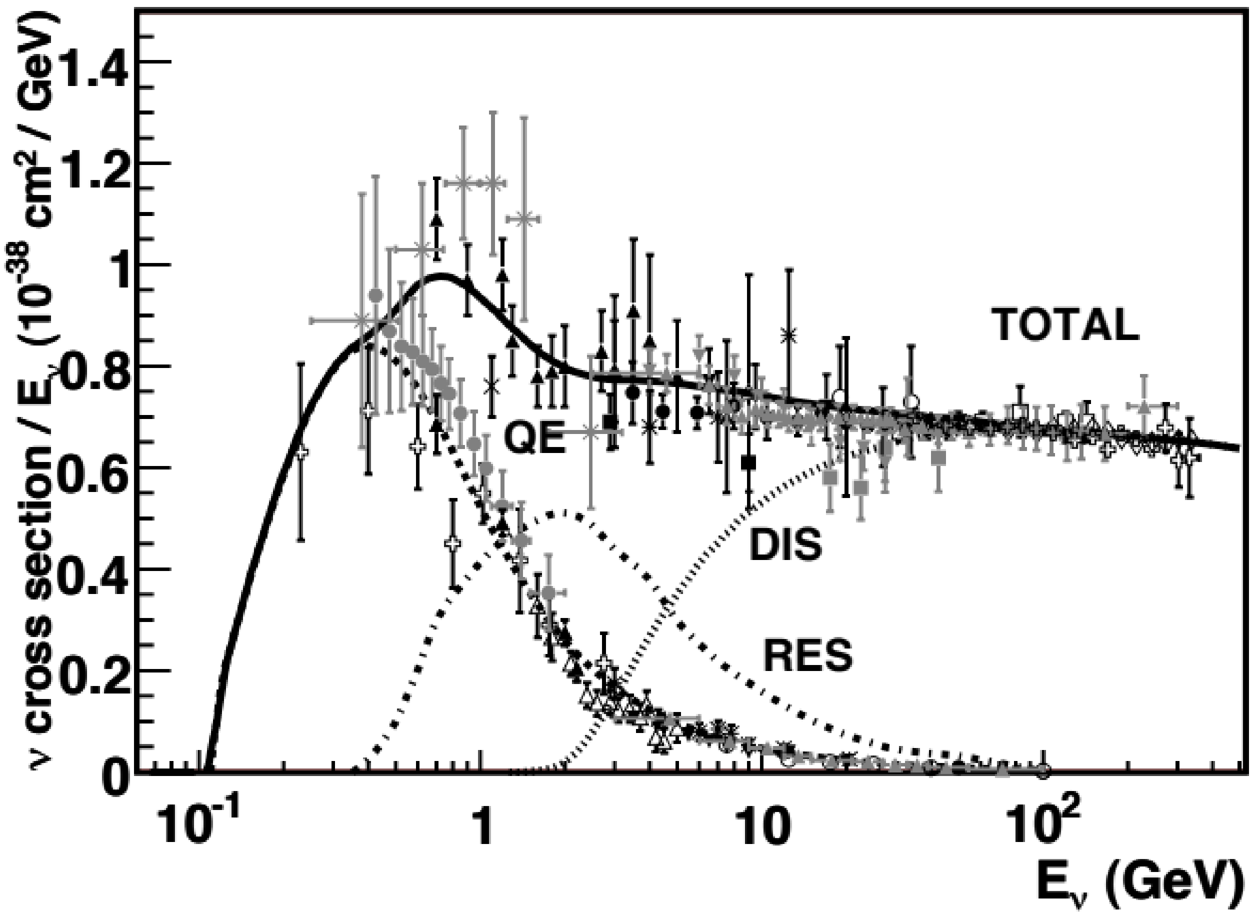
Accelerator experiments

One recent measurement (COHERENT)





Particle Data Group

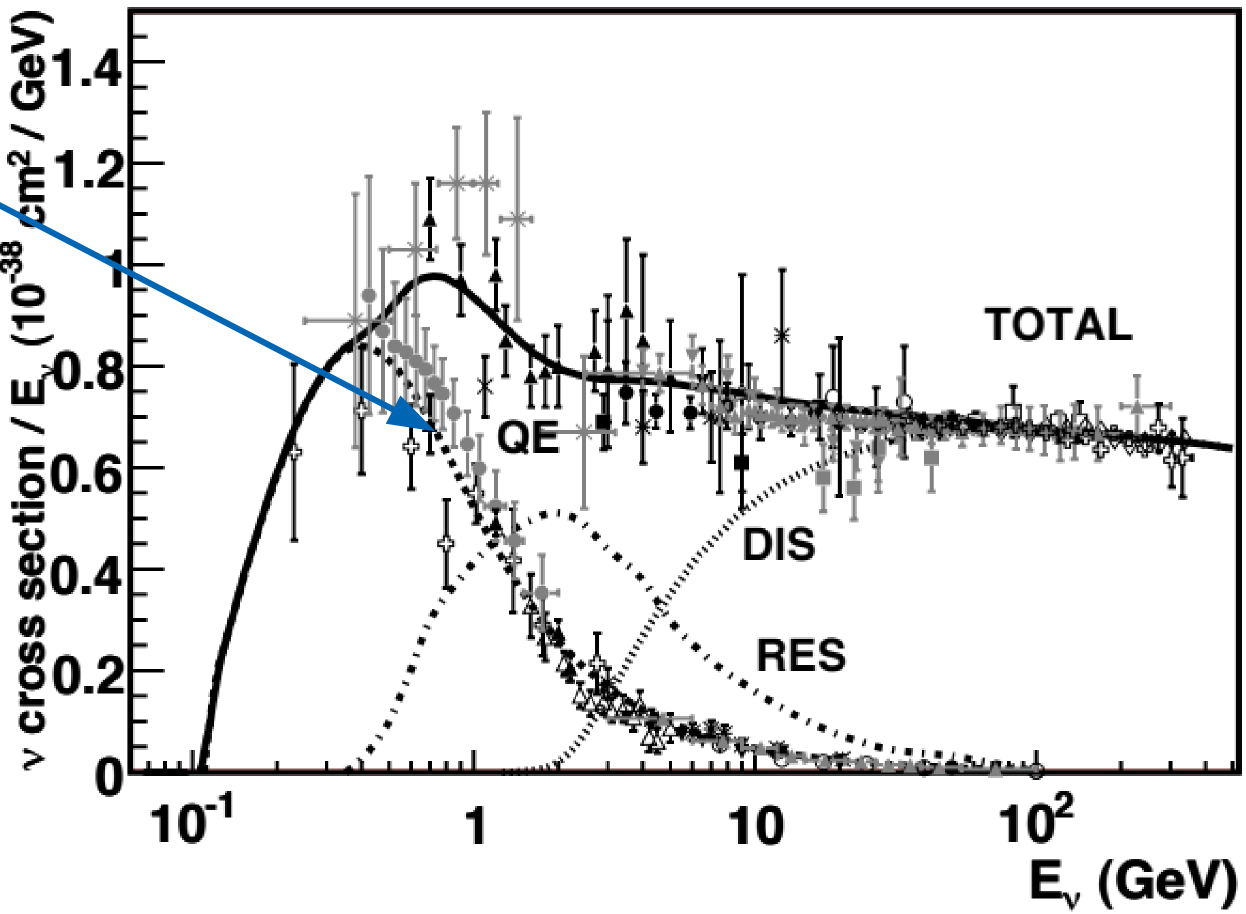


Particle Data Group

Quasi-elastic scattering:

$\nu_l + n \to l^- + p$

$\bar{\nu}_l + p \to l^+ + n$



Particle Data Group

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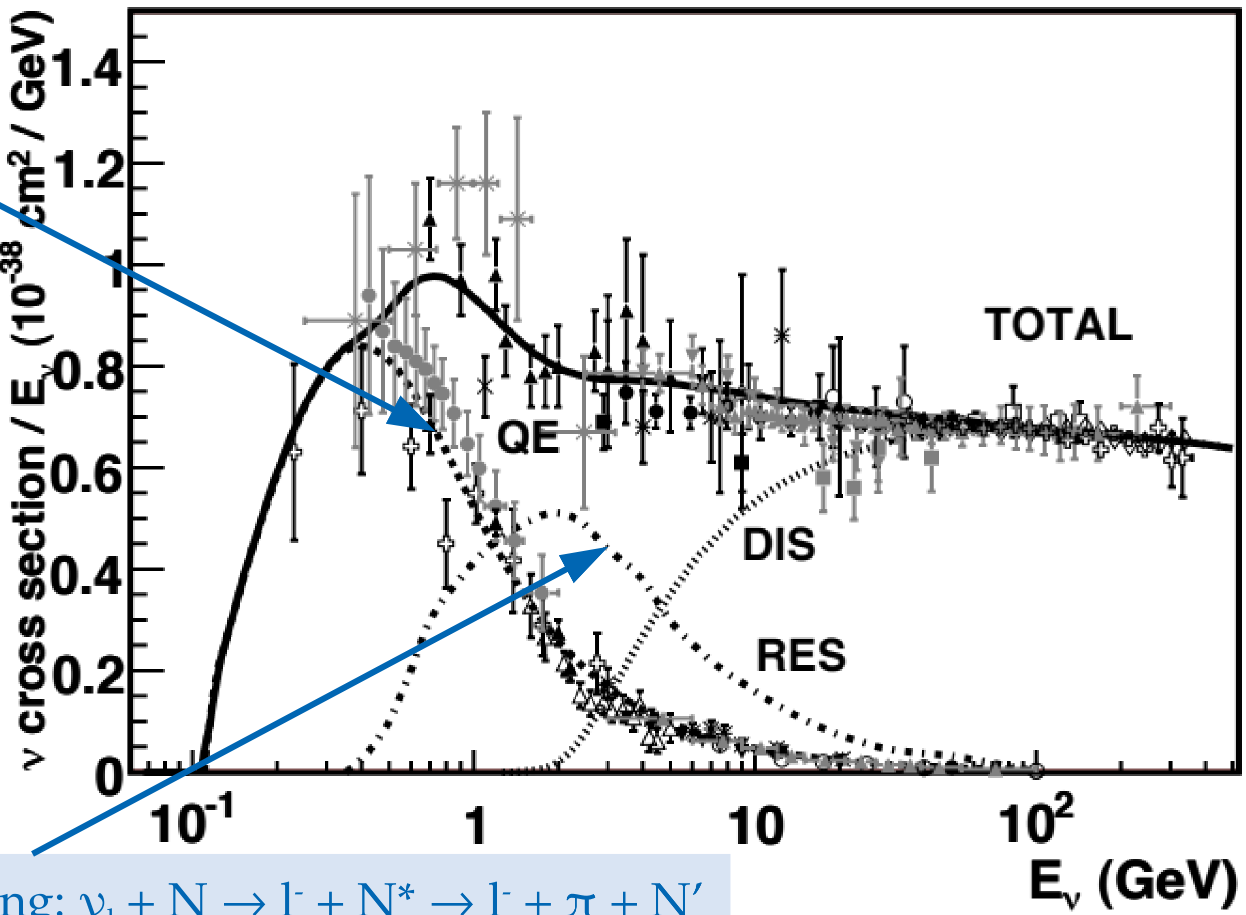


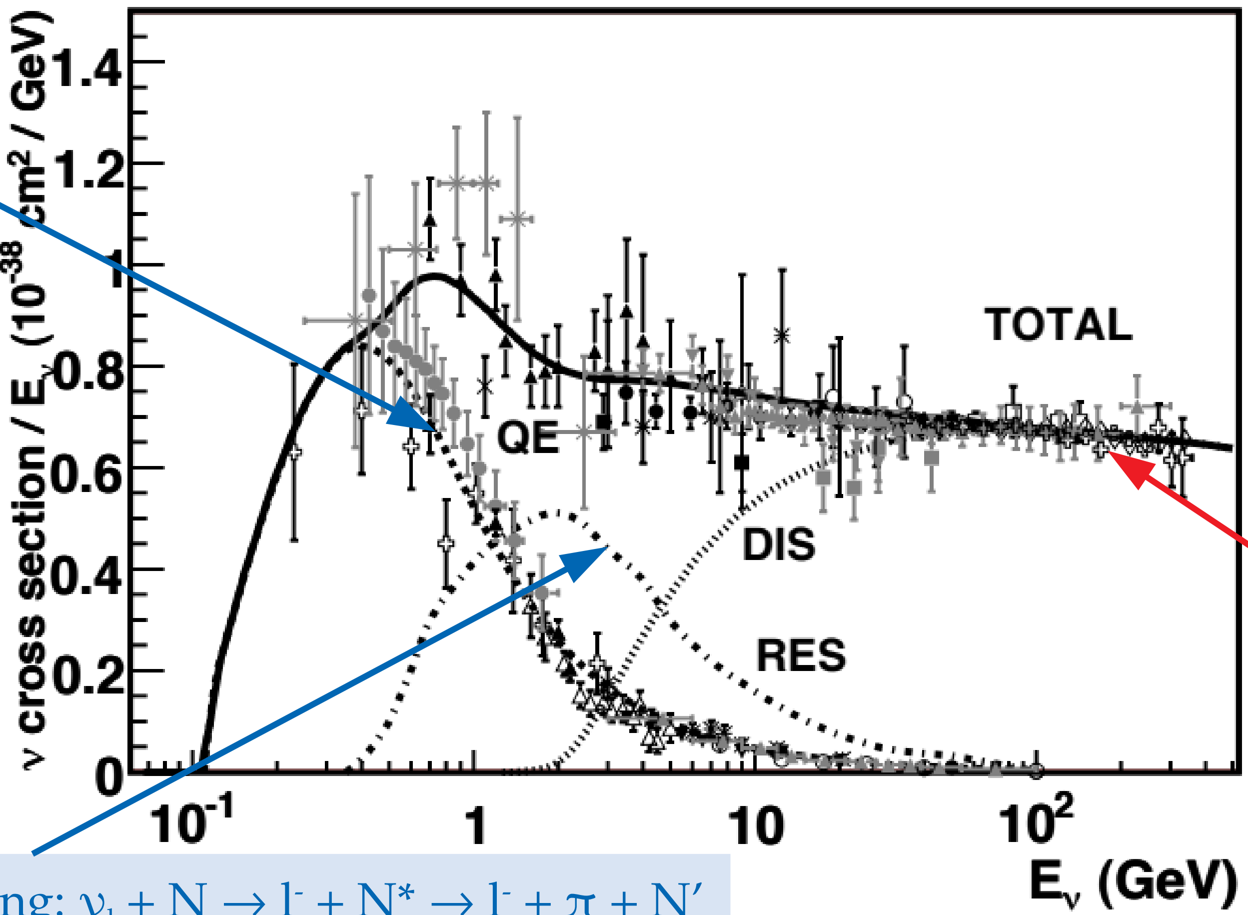
Resonant scattering: $\nu_l + N \to l^- + N^* \to l^- + \pi + N'$

Particle Data Group

Quasi-elastic scattering:

$\nu_l + n \rightarrow l^- + p$

$\bar{\nu}_l + p \rightarrow l^+ + n$



Deep inelastic scattering:

$\nu_l + N \rightarrow l^- + X$

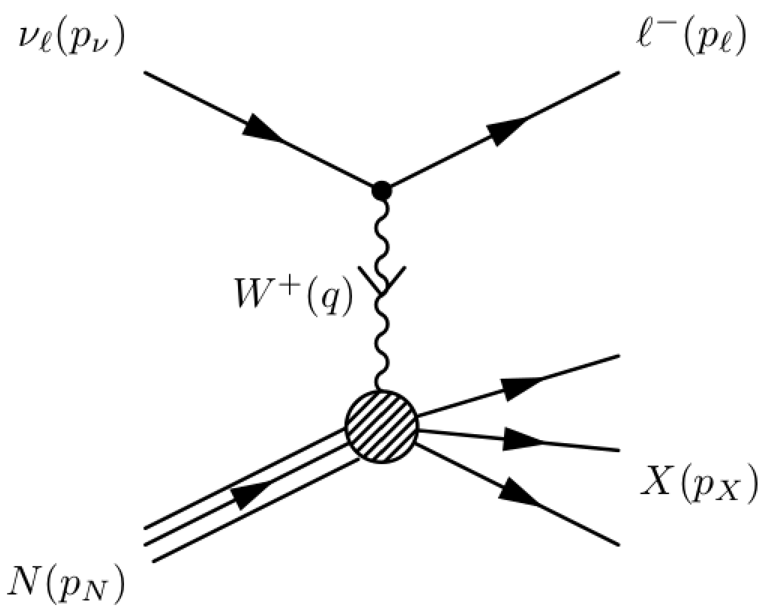
$\bar{\nu}_l + N \rightarrow l^+ + X$

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

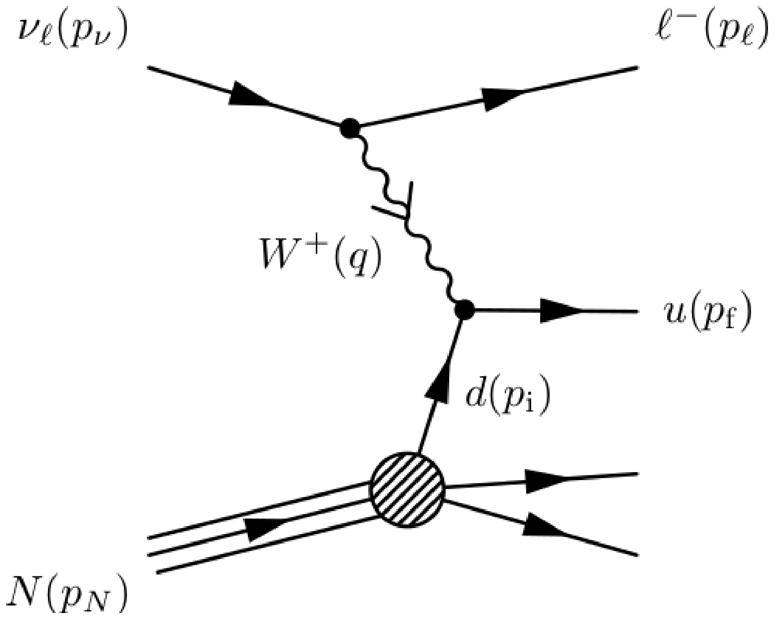
Particle Data Group

How does DIS probe nucleon structure?

What you see

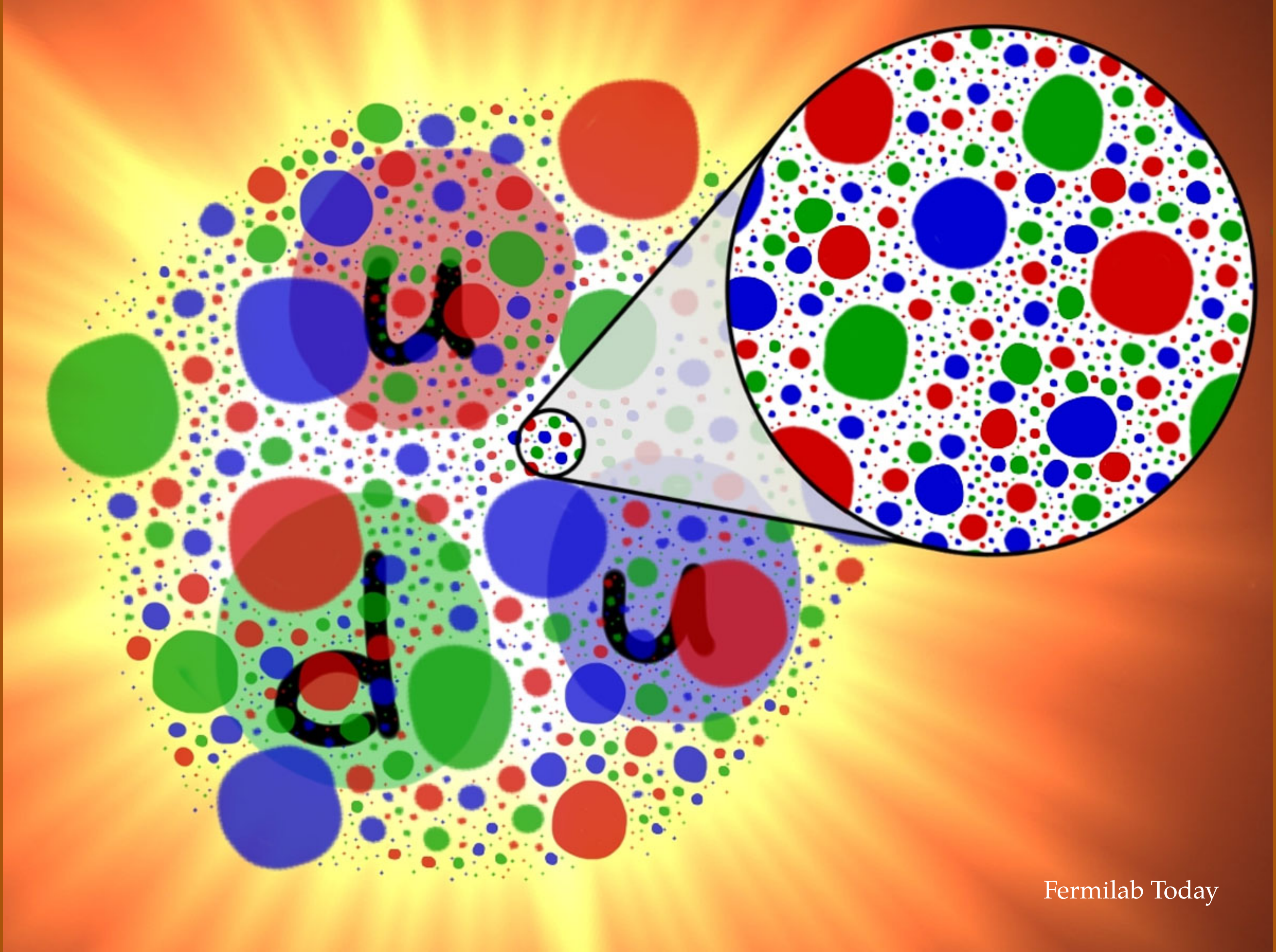


Beneath the hood



(Plus the equivalent neutral-current process (Z-exchange))

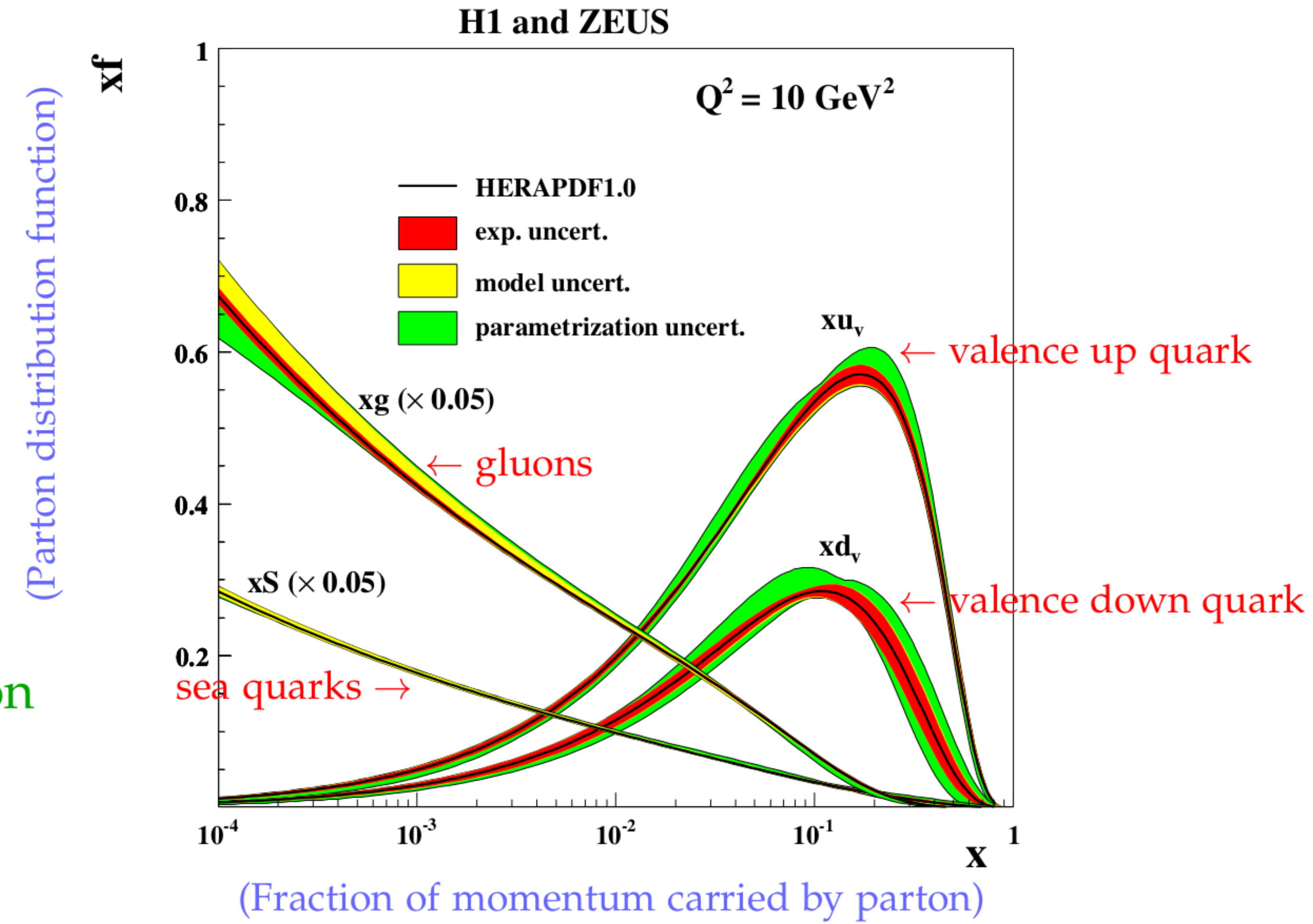
Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*



Fermilab Today

Peeking inside a proton

← Extrapolation



A. Cooper-Sarkar 2012

Extrapolating the cross section to high energies

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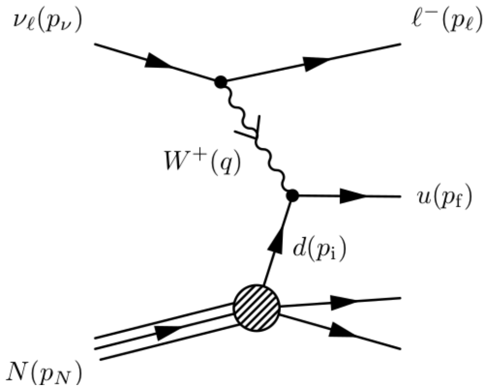
SM



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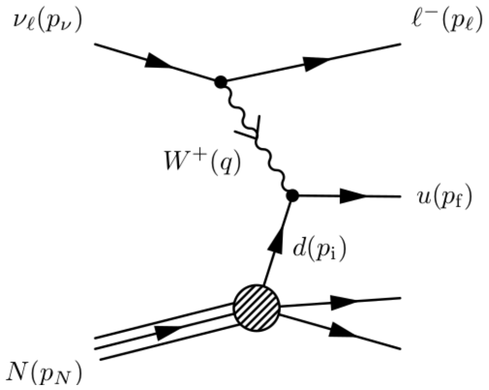
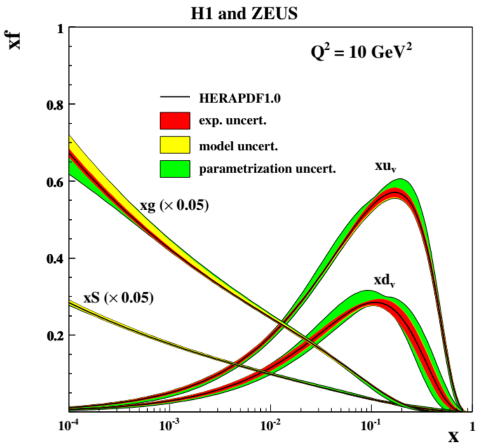


+

PDFs



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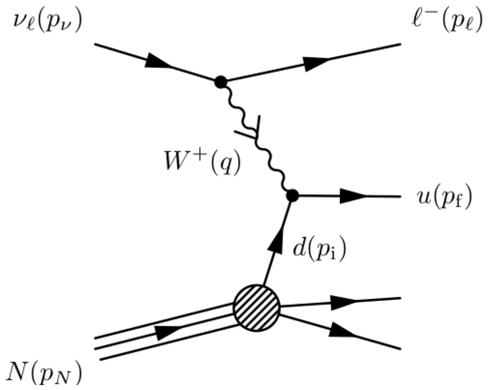

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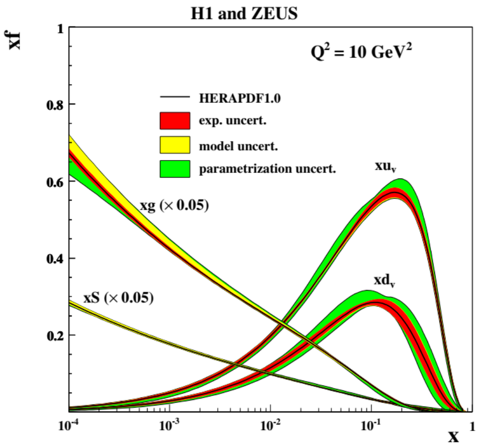

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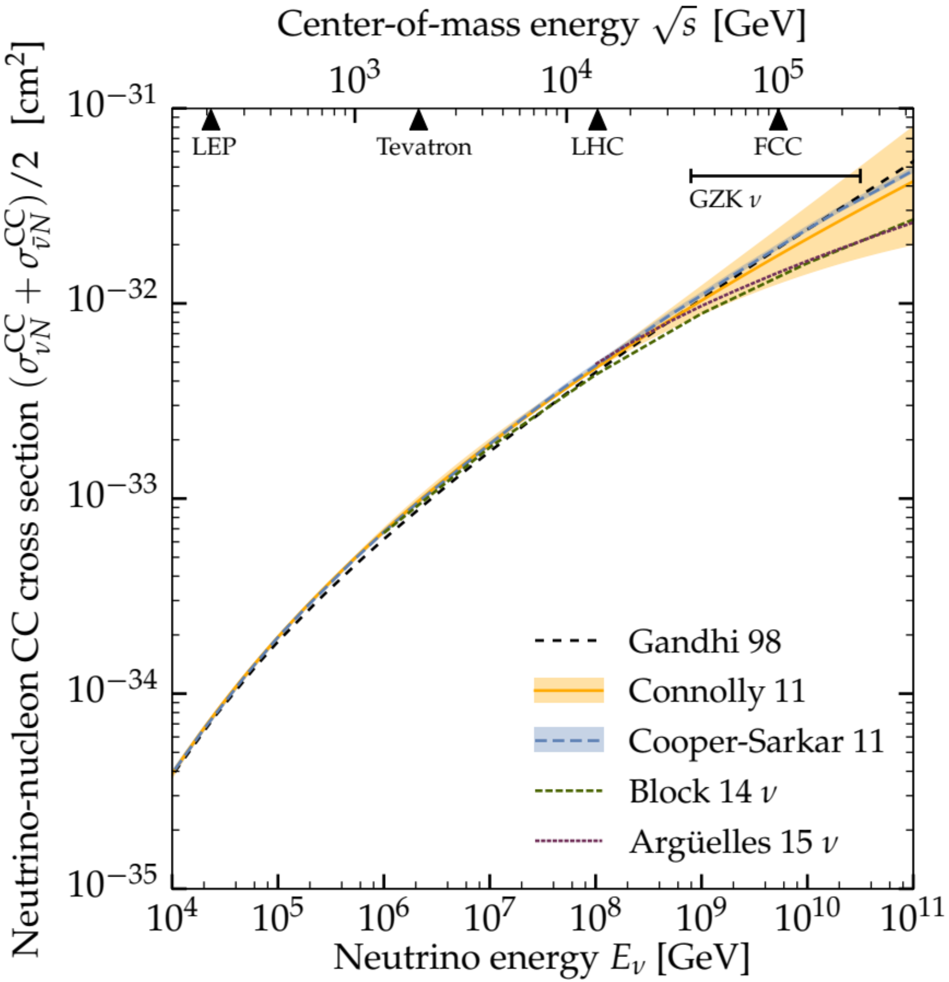
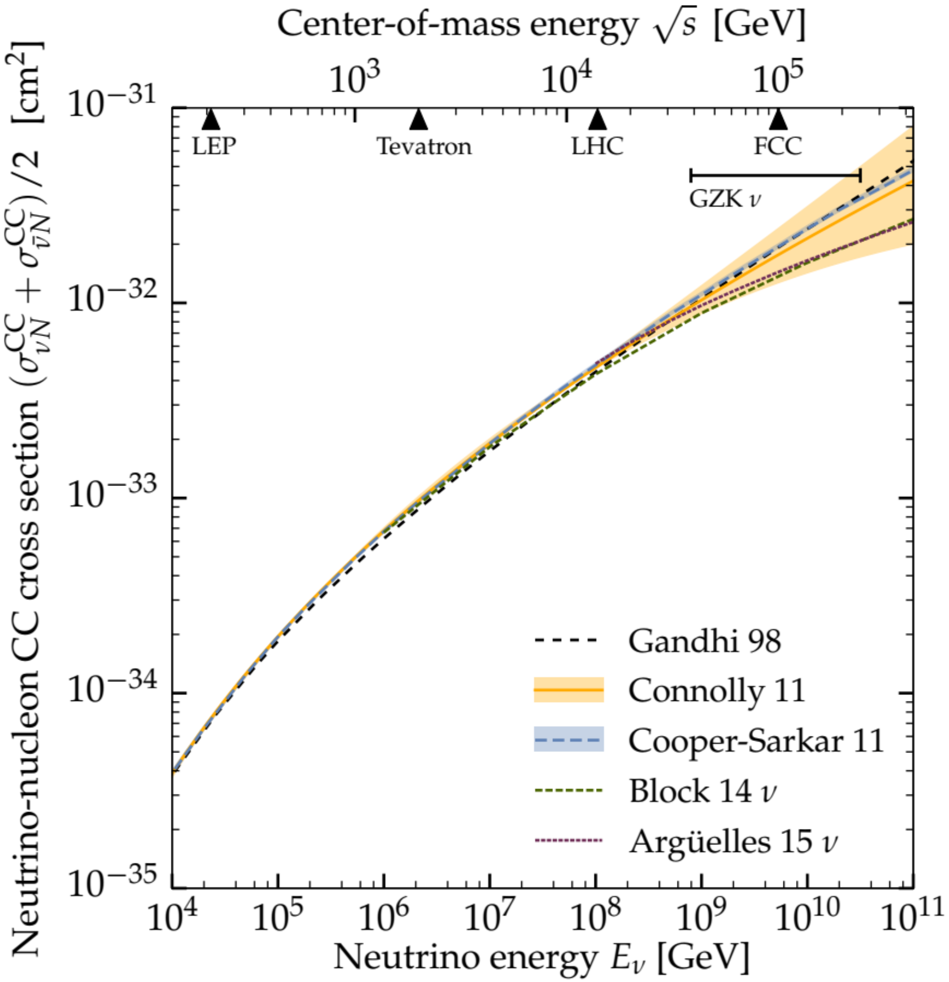


What can we measure *now* and later?



MB & A. Connolly, 1711.11043

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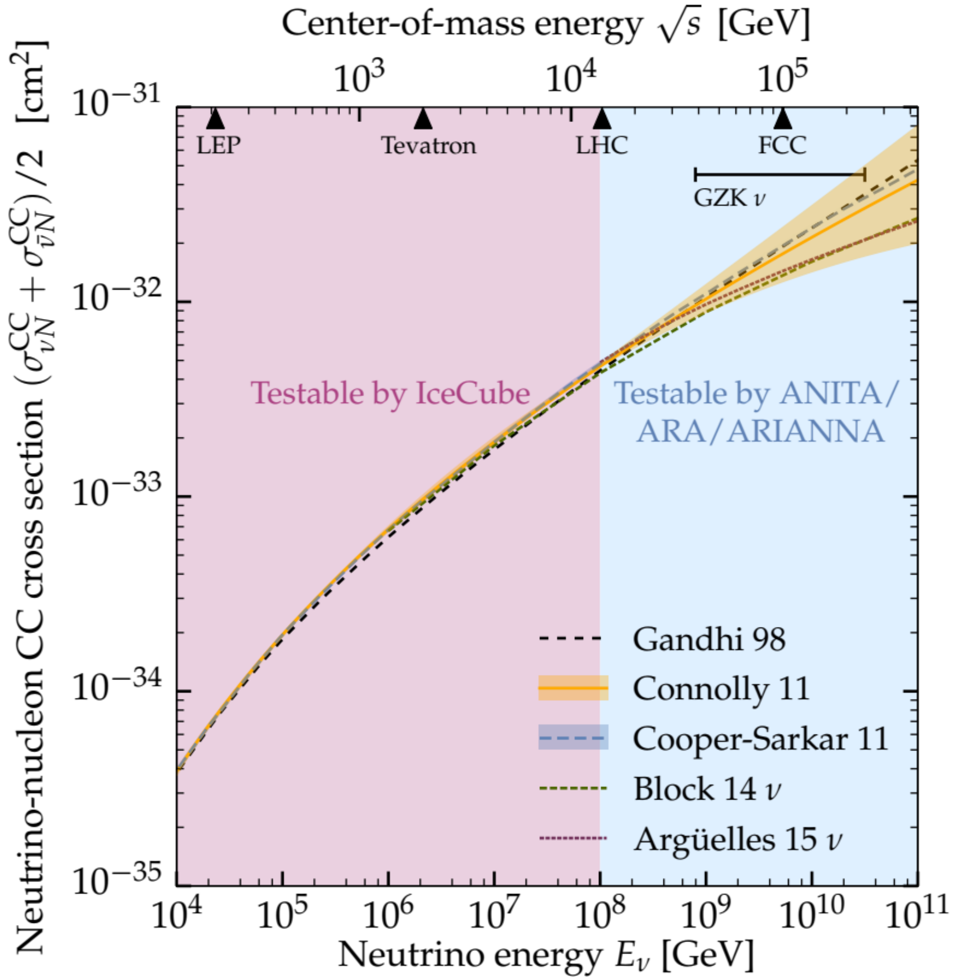

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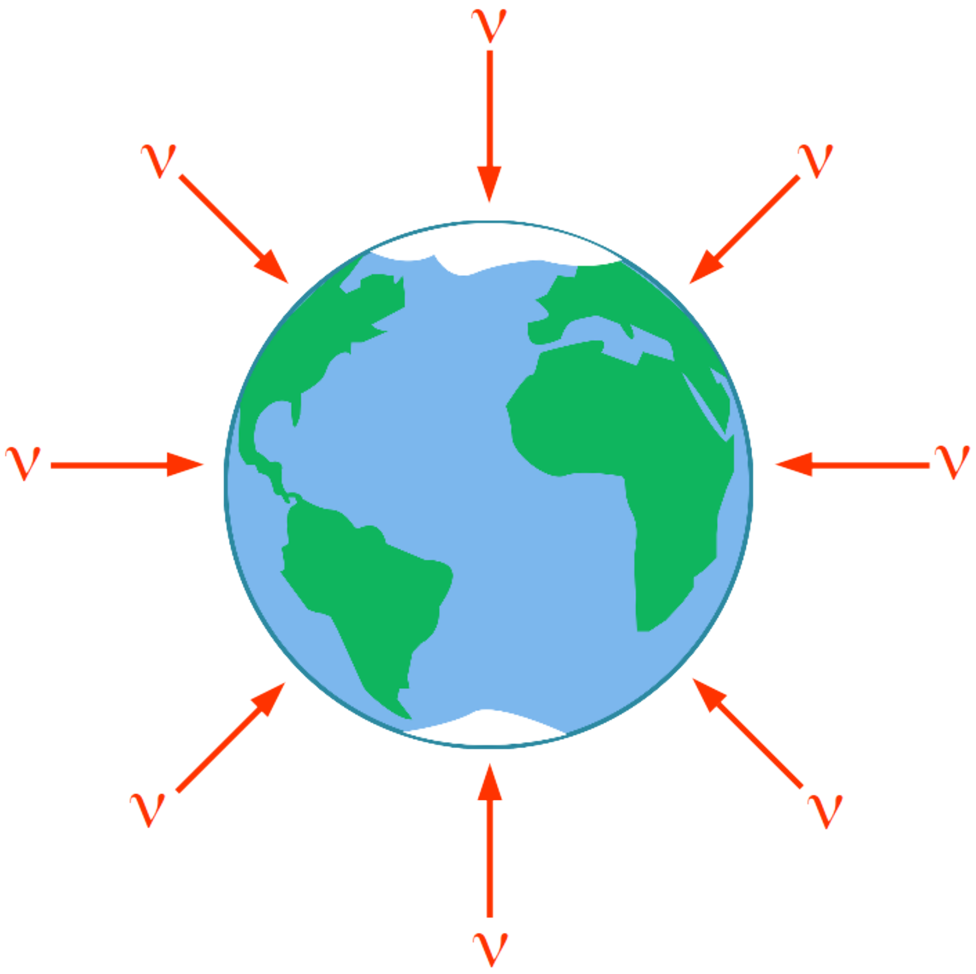
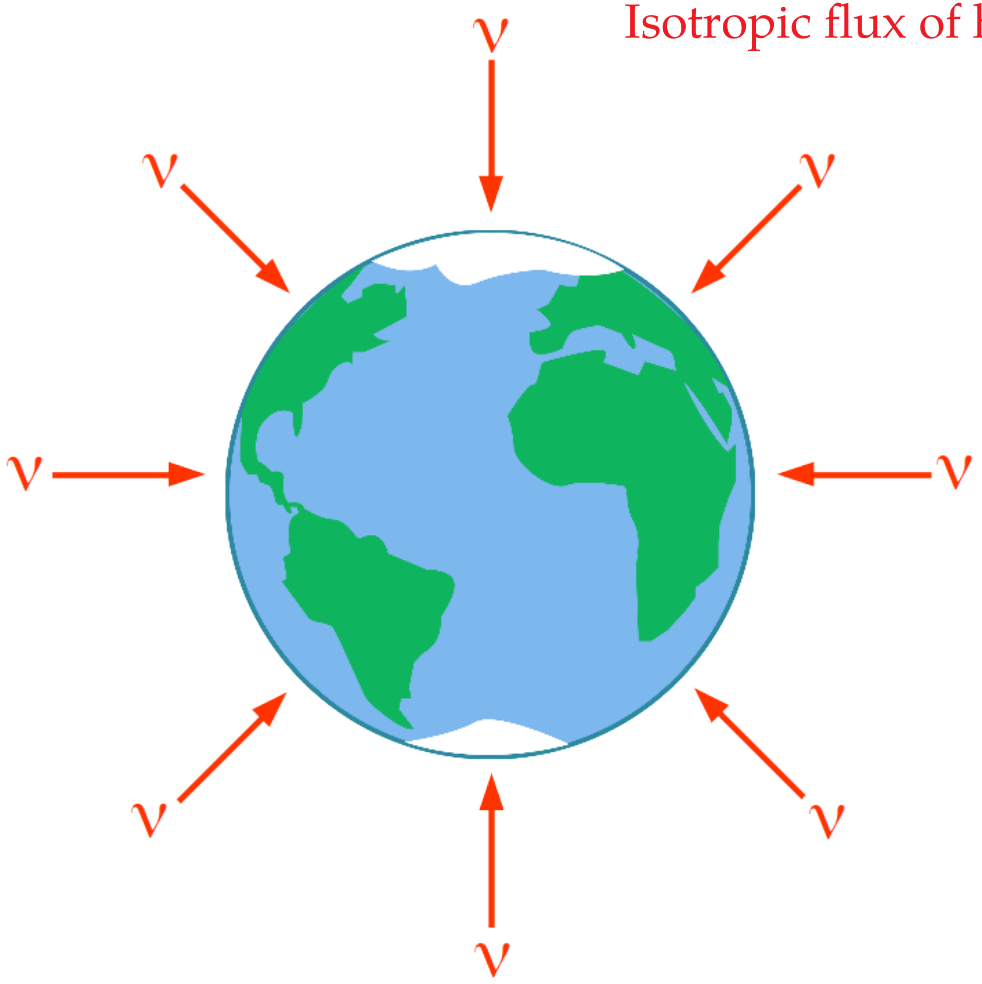
Neutrino, interrupted

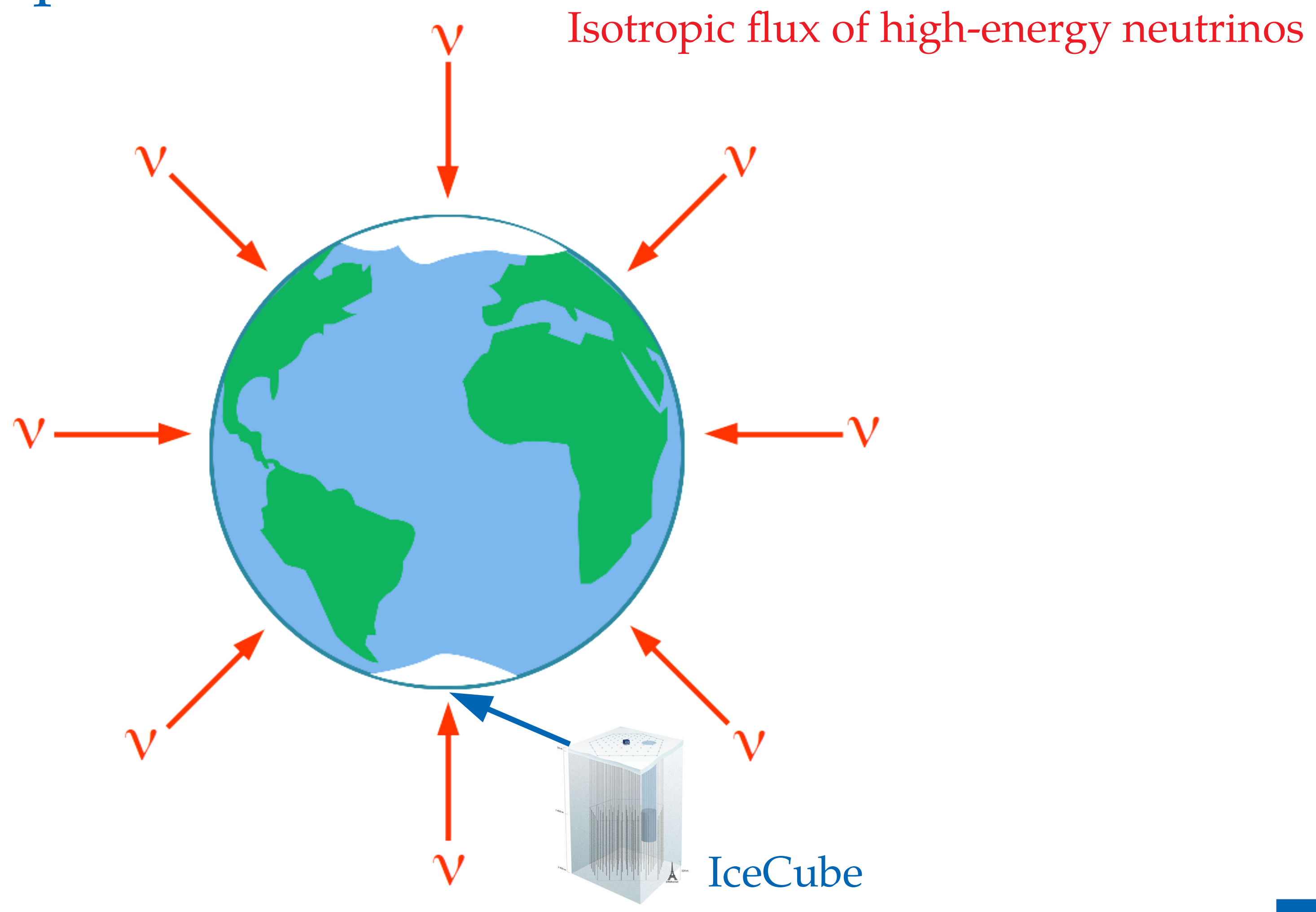


Neutrino, interrupted

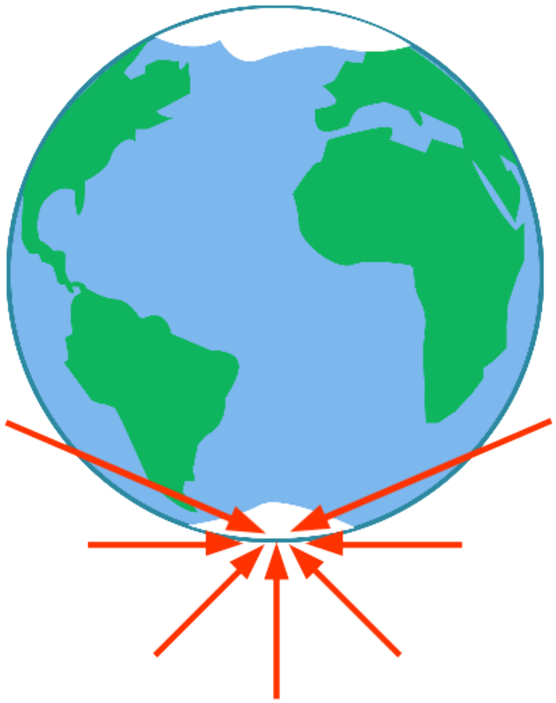
Isotropic flux of high-energy neutrinos



Neutrino, interrupted

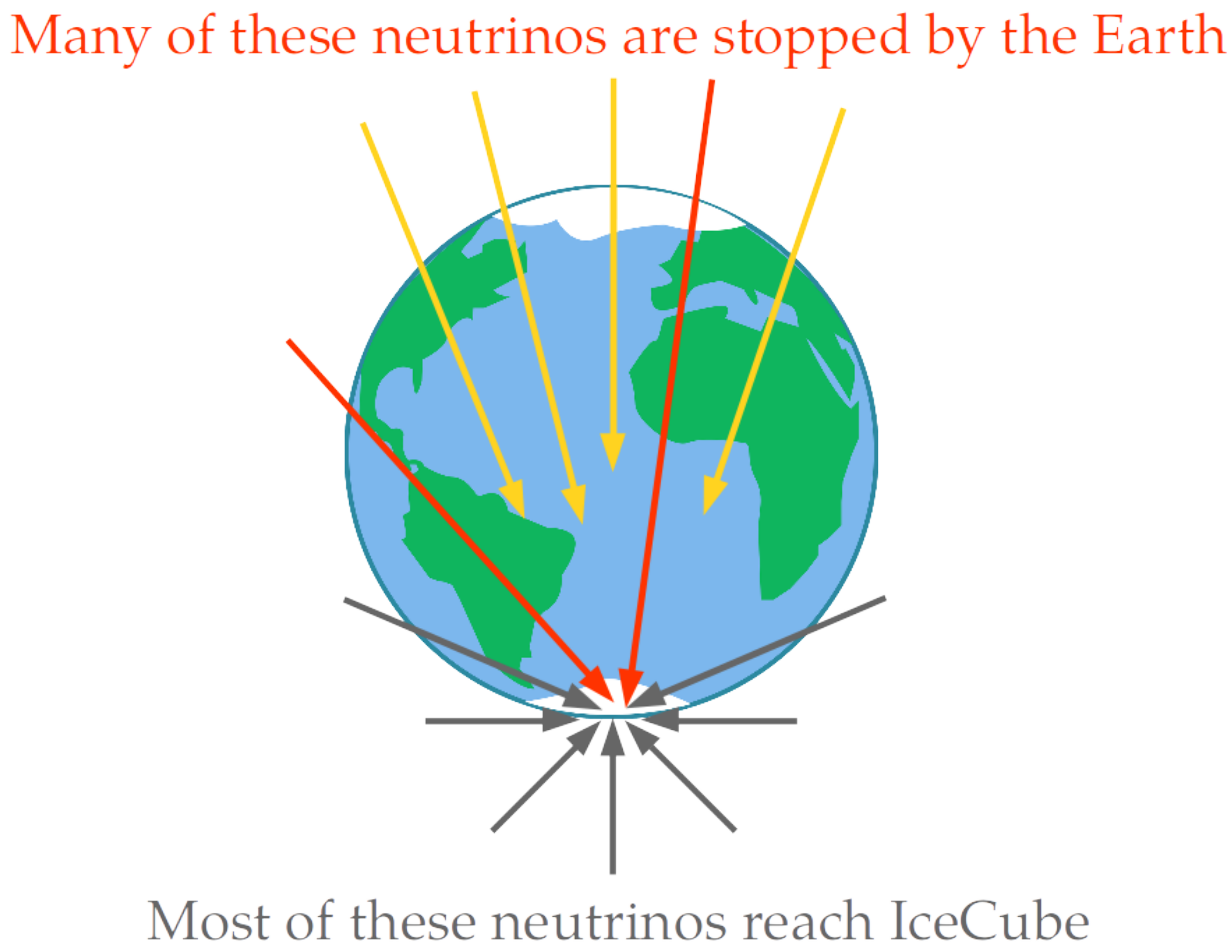


Neutrino, interrupted



Most of these neutrinos reach IceCube

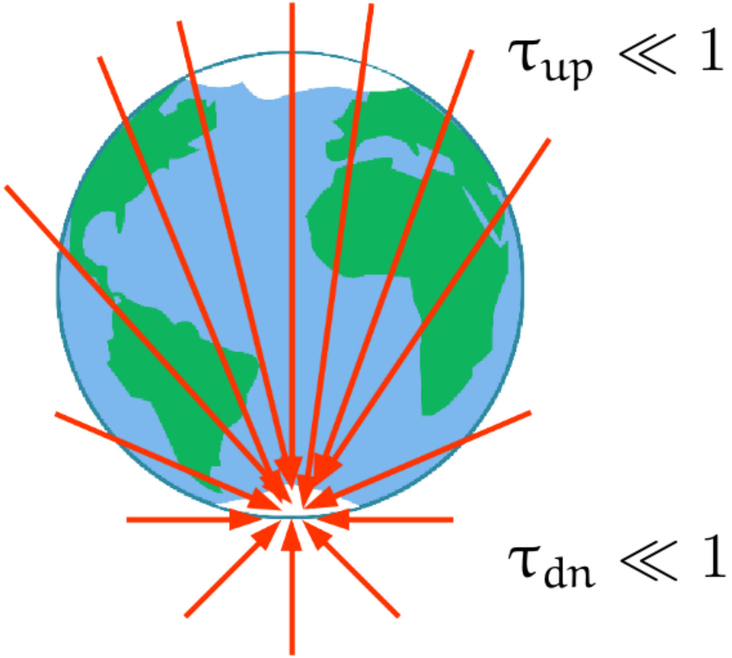
Neutrino, interrupted



Measuring the high-energy cross section

$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



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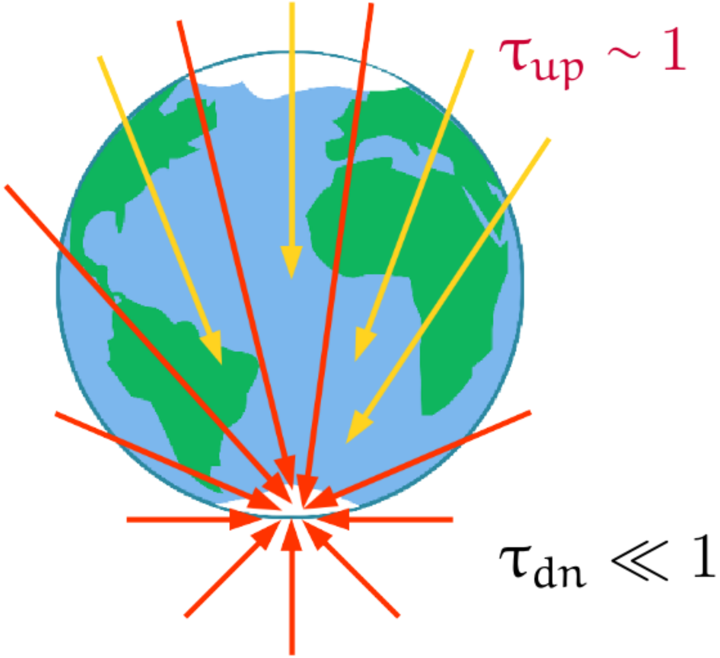

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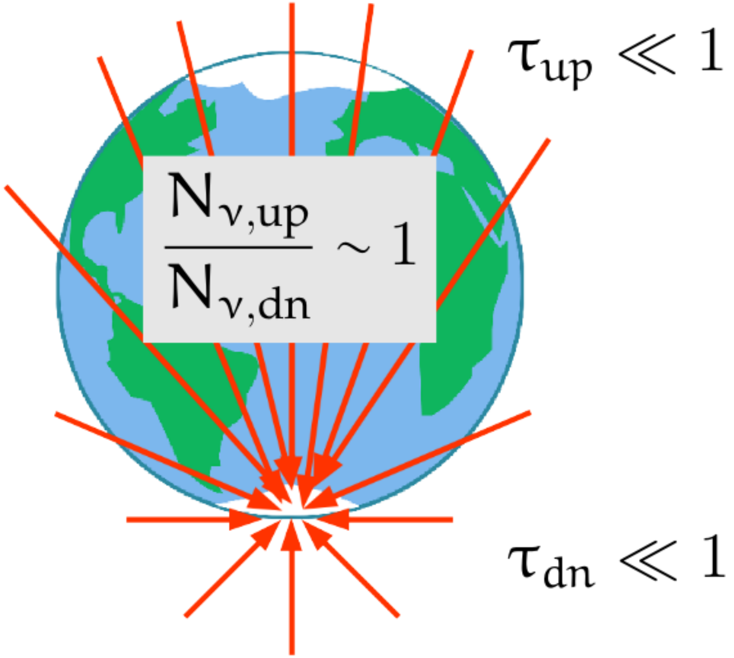

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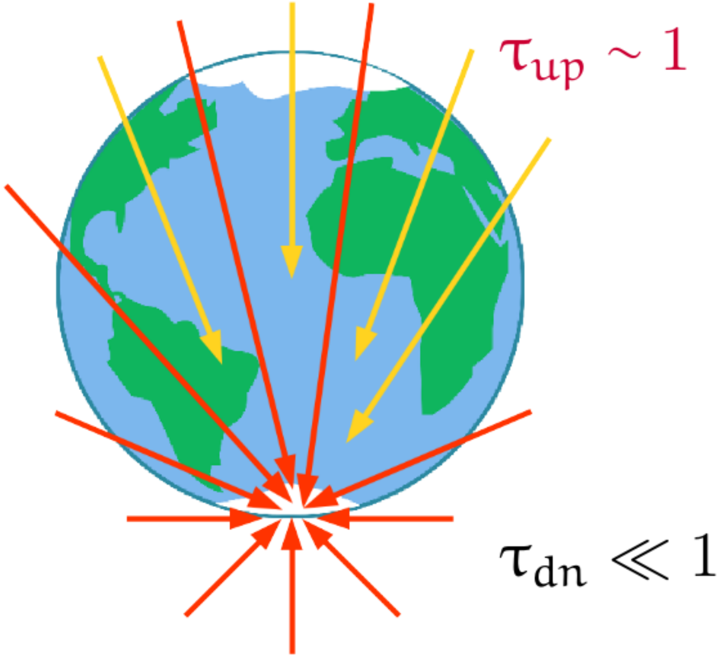

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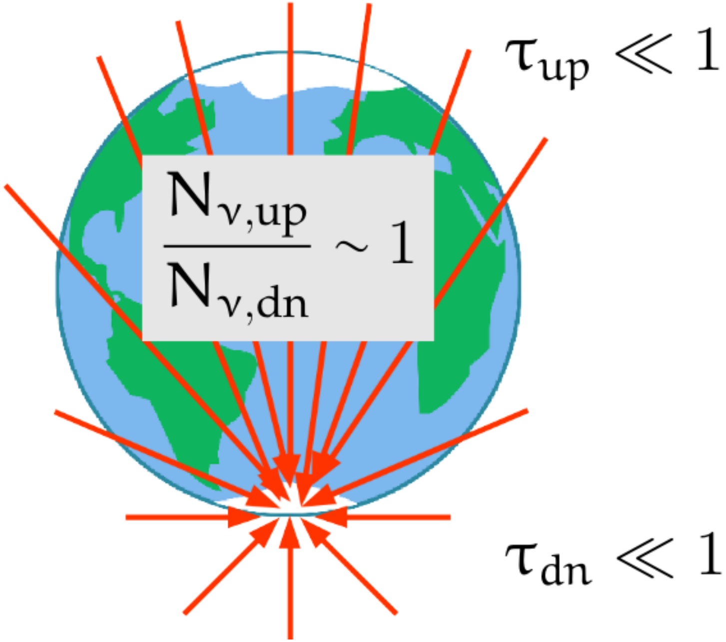

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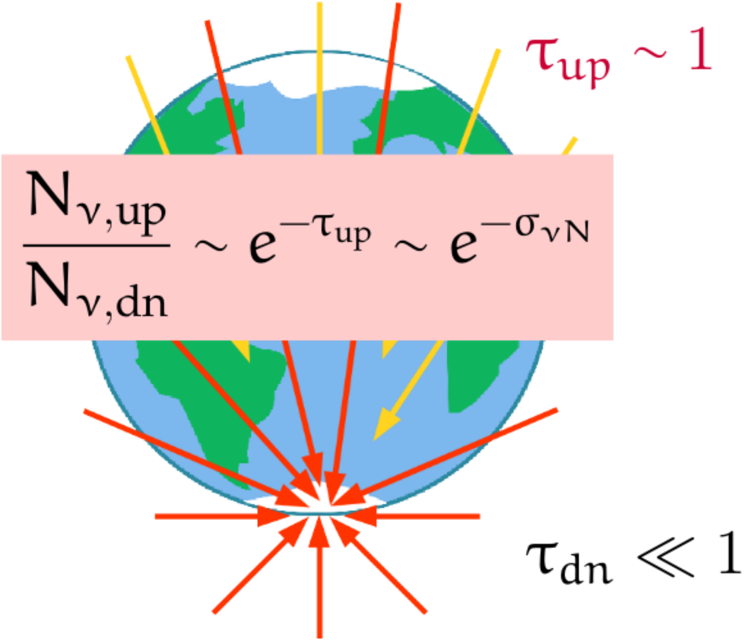
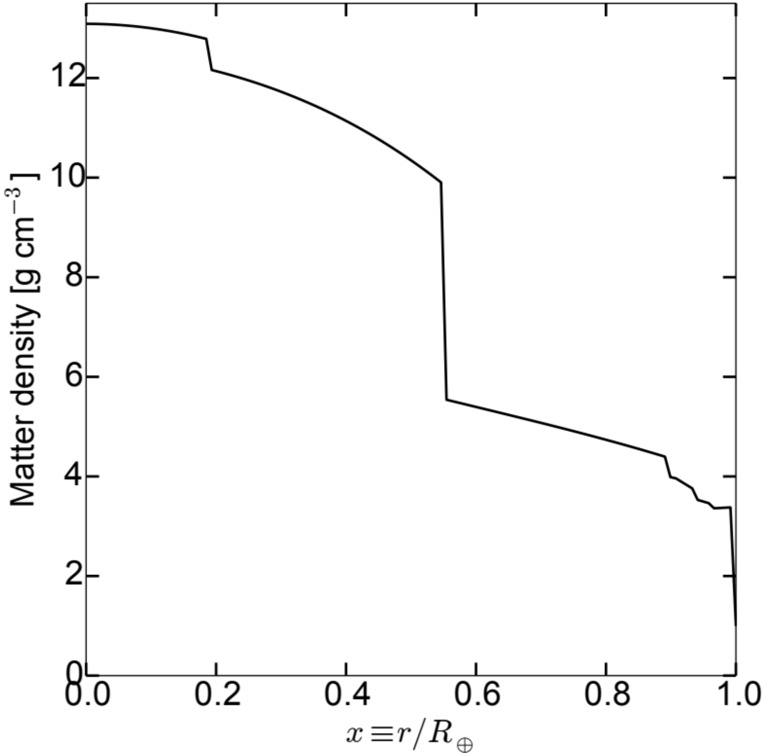


A feel for the in-Earth attenuation

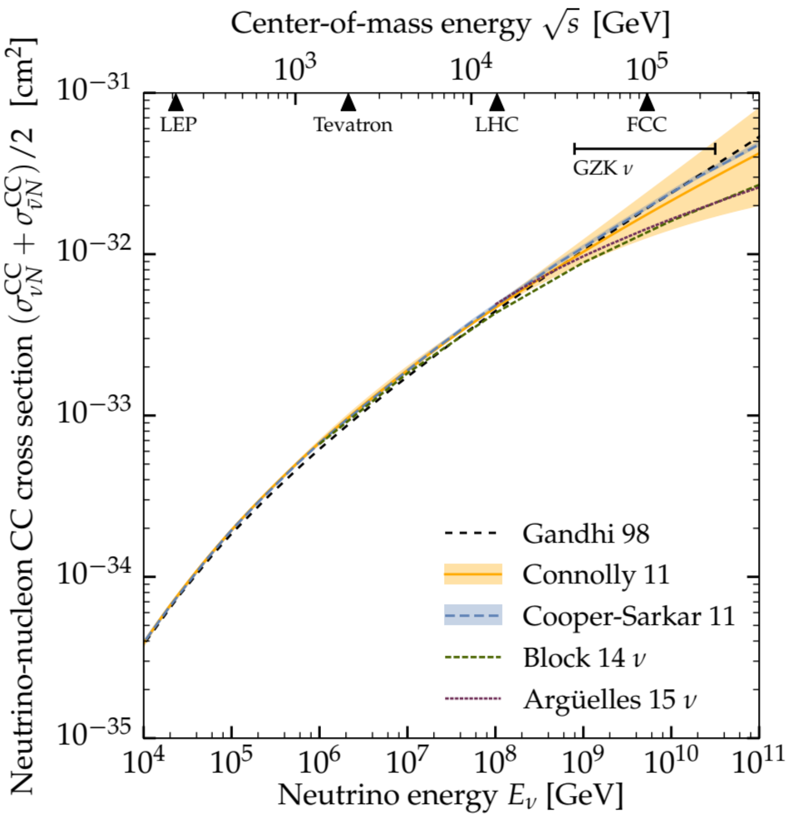
Earth matter density

(Preliminary Reference Earth Model)



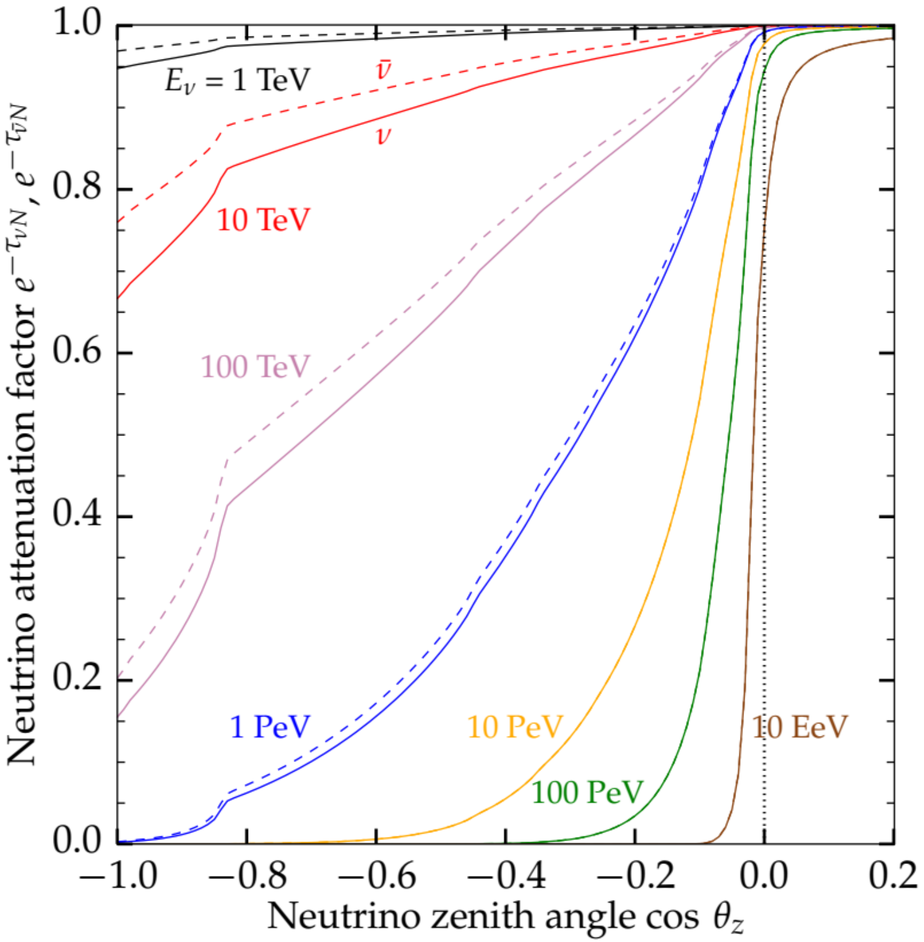
+

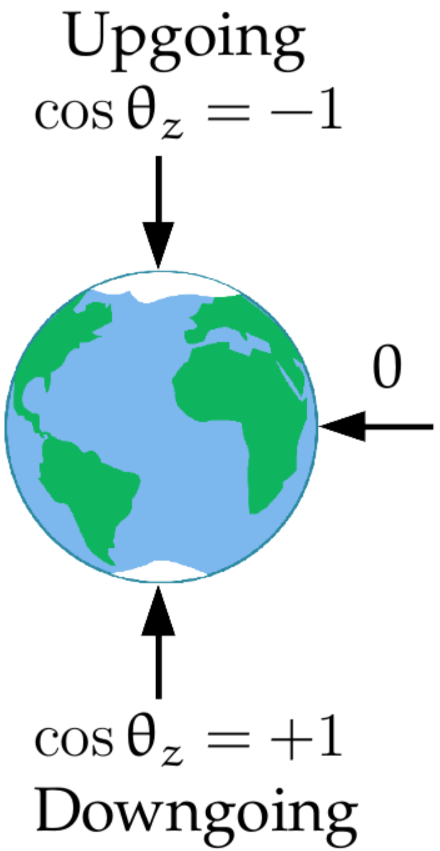
Neutrino-nucleon cross section

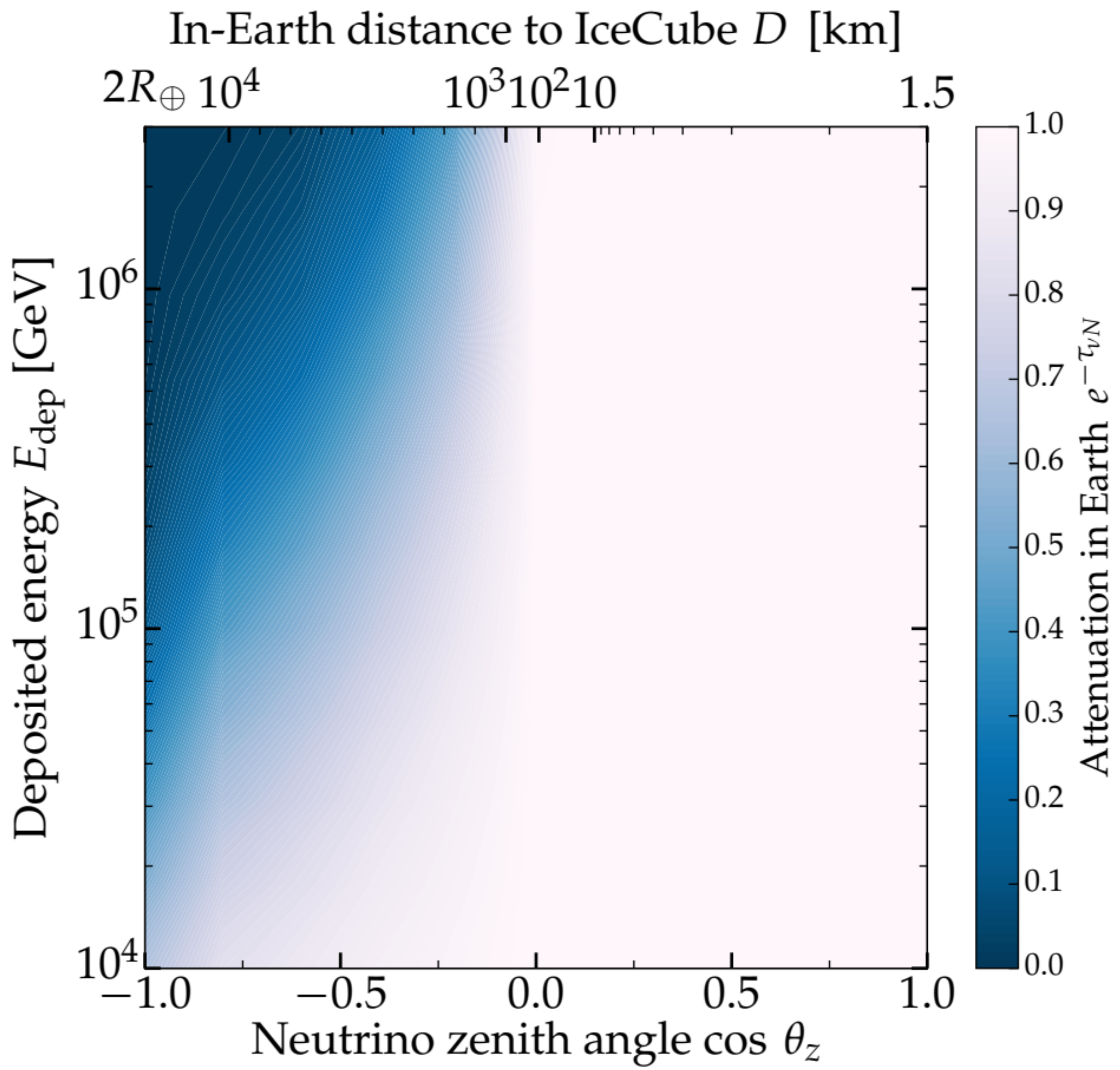


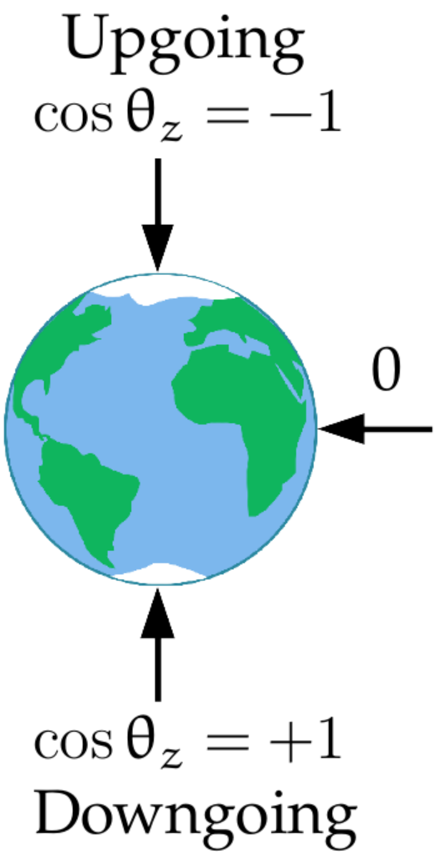
A feel for the in-Earth attenuation

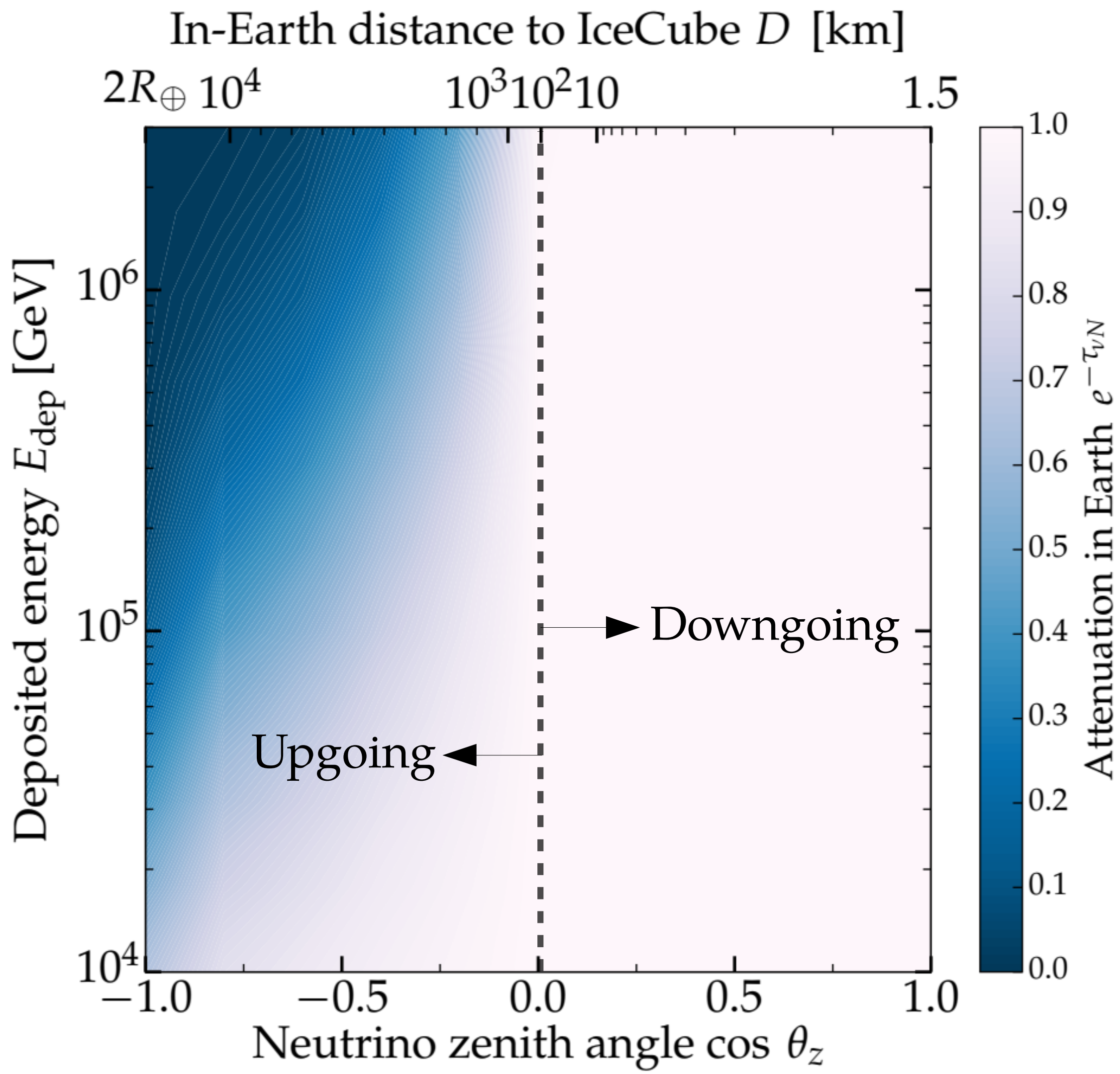
=






In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^4
10^5
10^6
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing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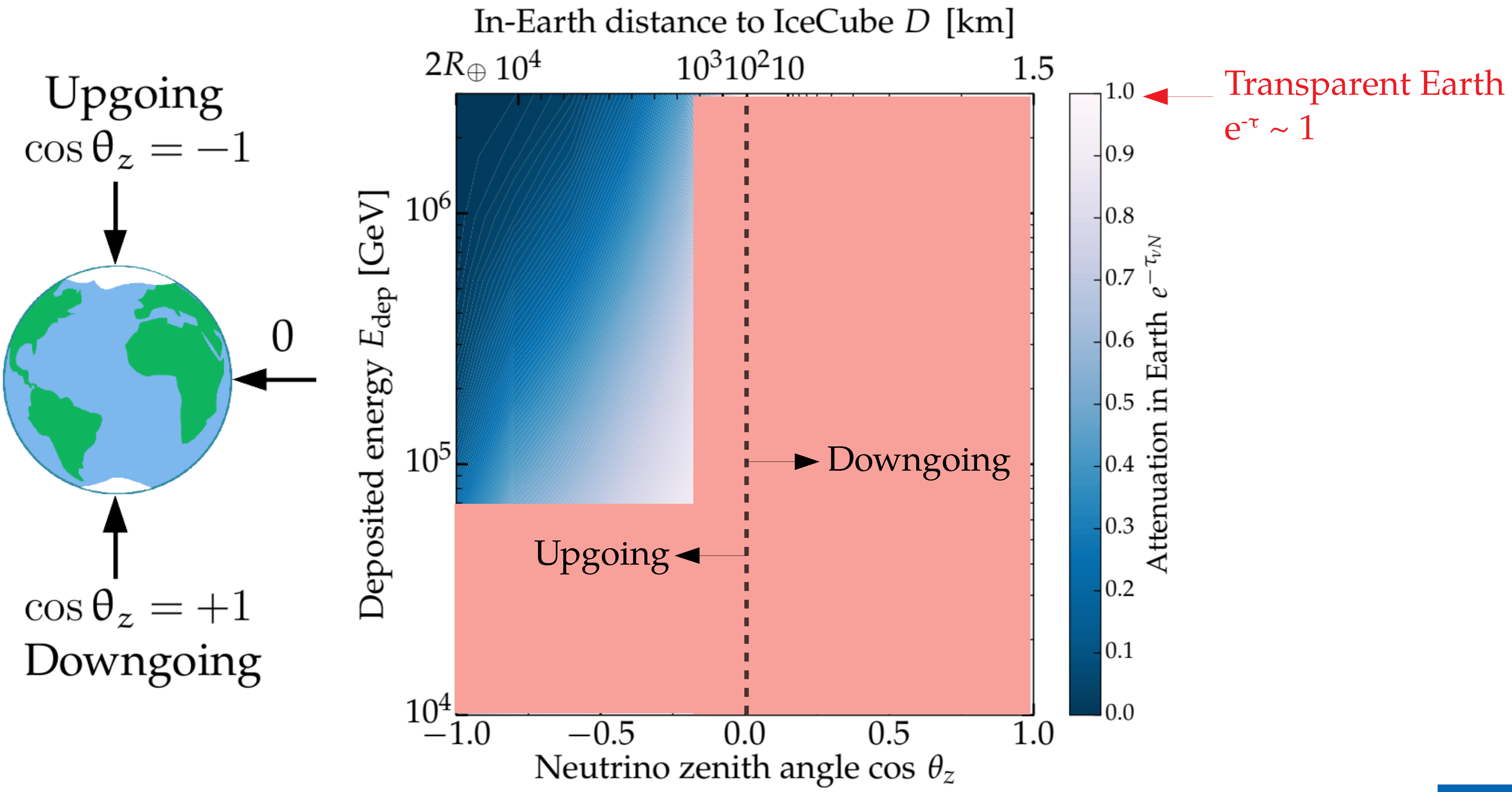
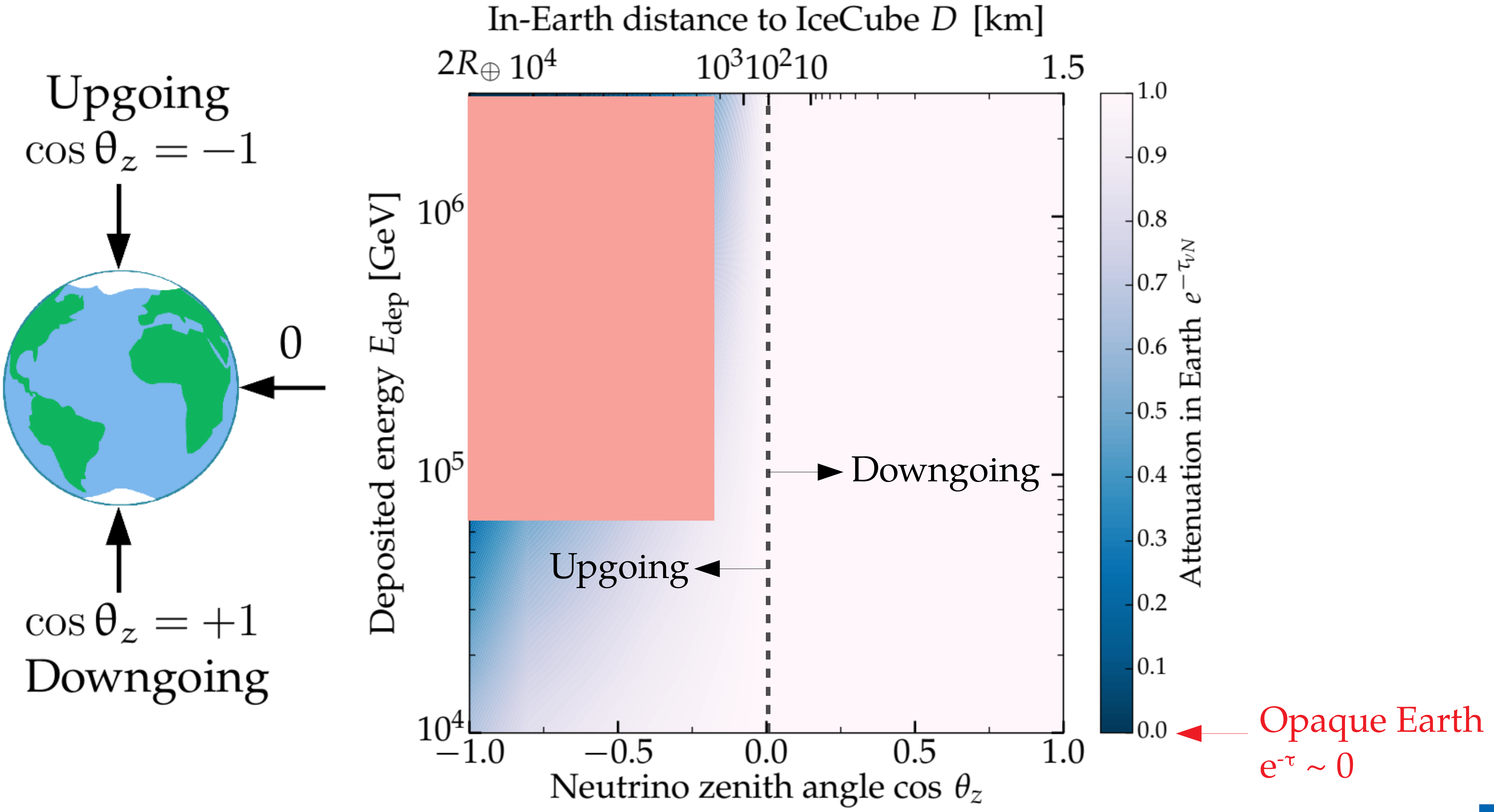
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0

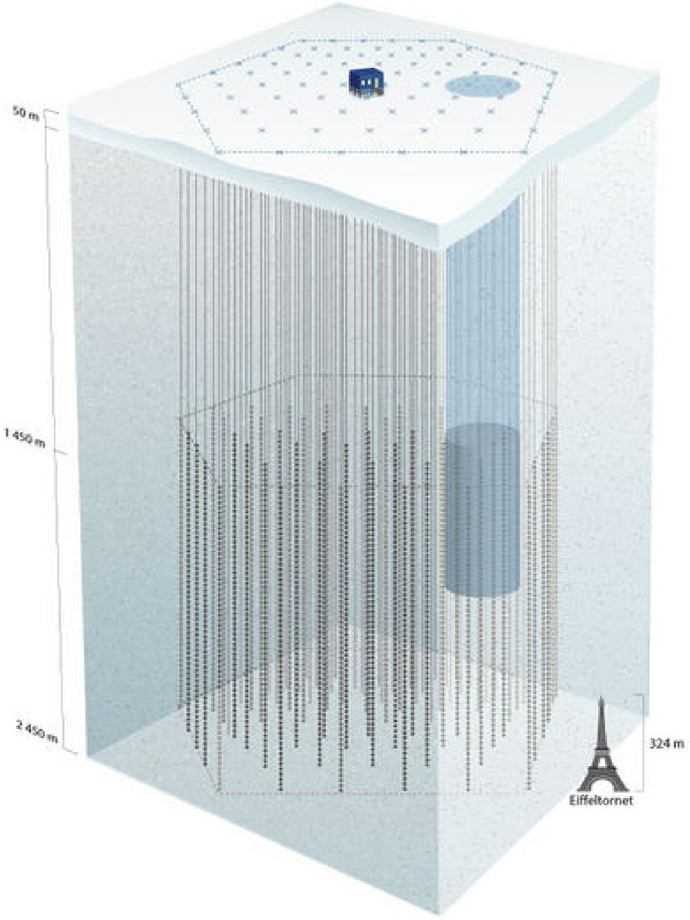


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Transparent Earth
$e^{-\tau} \sim 1$



Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Opaque Earth
$e^{-\tau} \sim 0$

IceCube – What is it?



- Km^3 in-ice Cherenkov detector in Antarctica
- >5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

How does IceCube see neutrinos?

Two types of fundamental interactions …

Charged-current (CC)

$$\nu_l + N \to l + \text{hadrons}$$

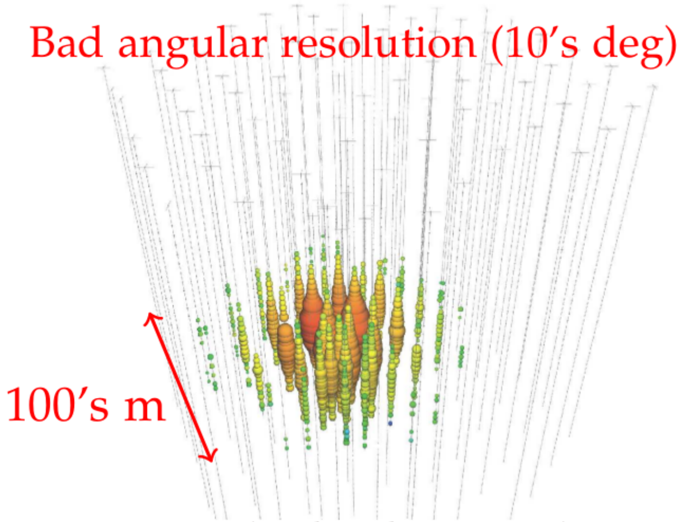
Neutral-current (NC)

$$\nu_l + N \to \nu_l + \text{hadrons}$$

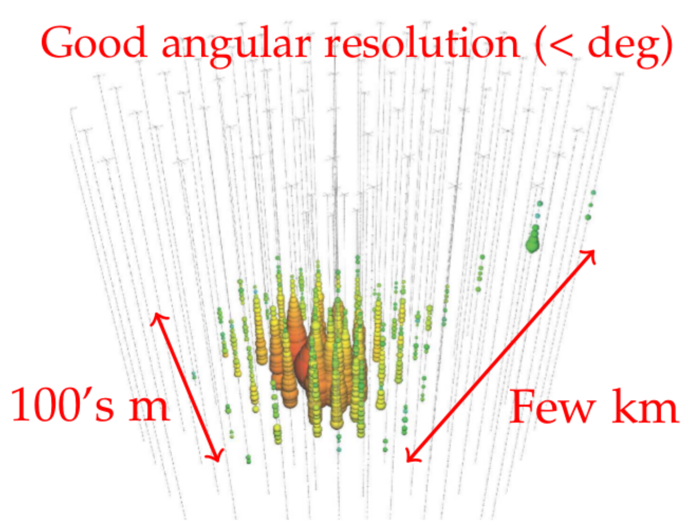
These shower and make light

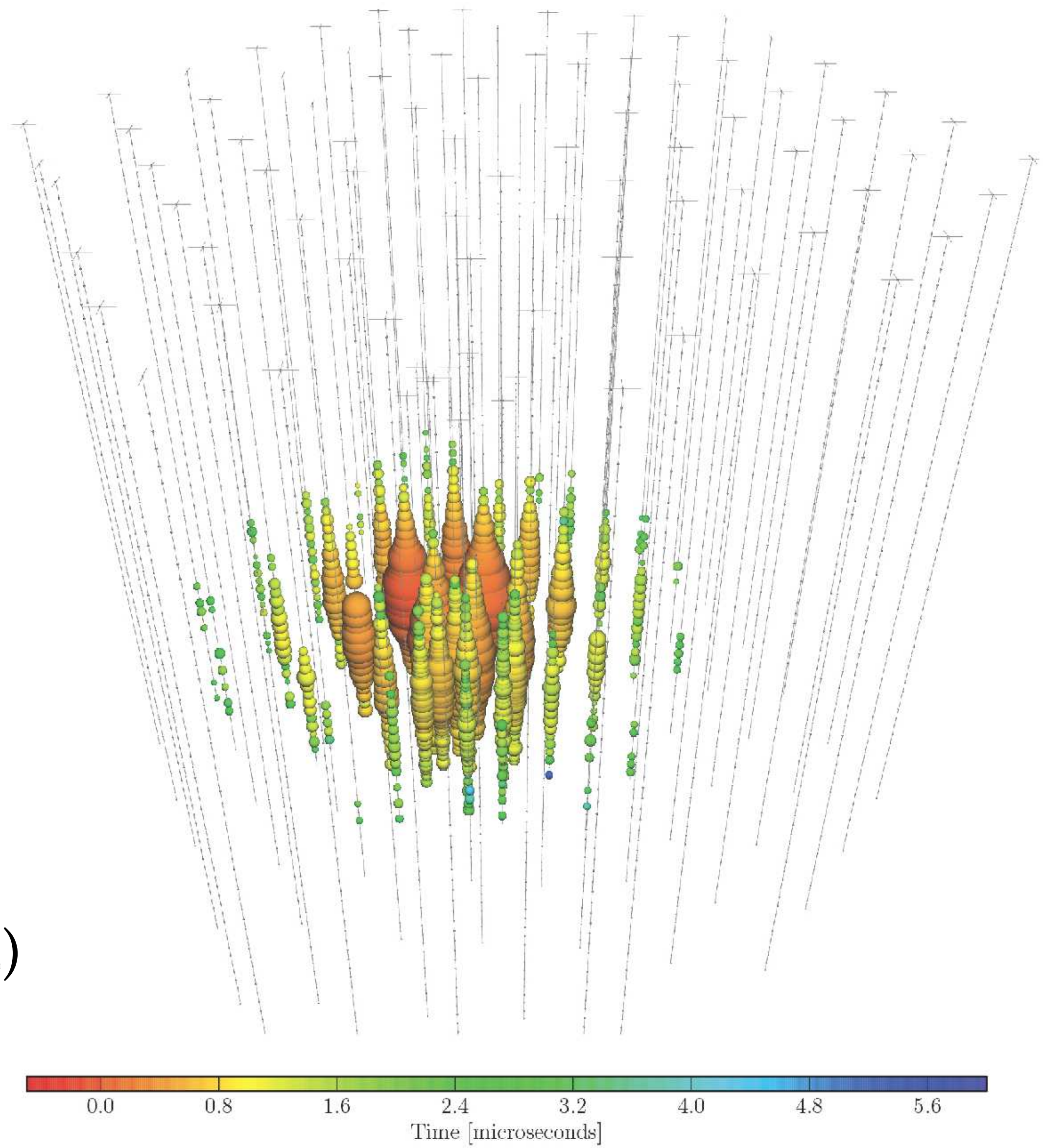
… create two event topologies …

Showers — From CC ν_e or ν_τ, or NC ν_x



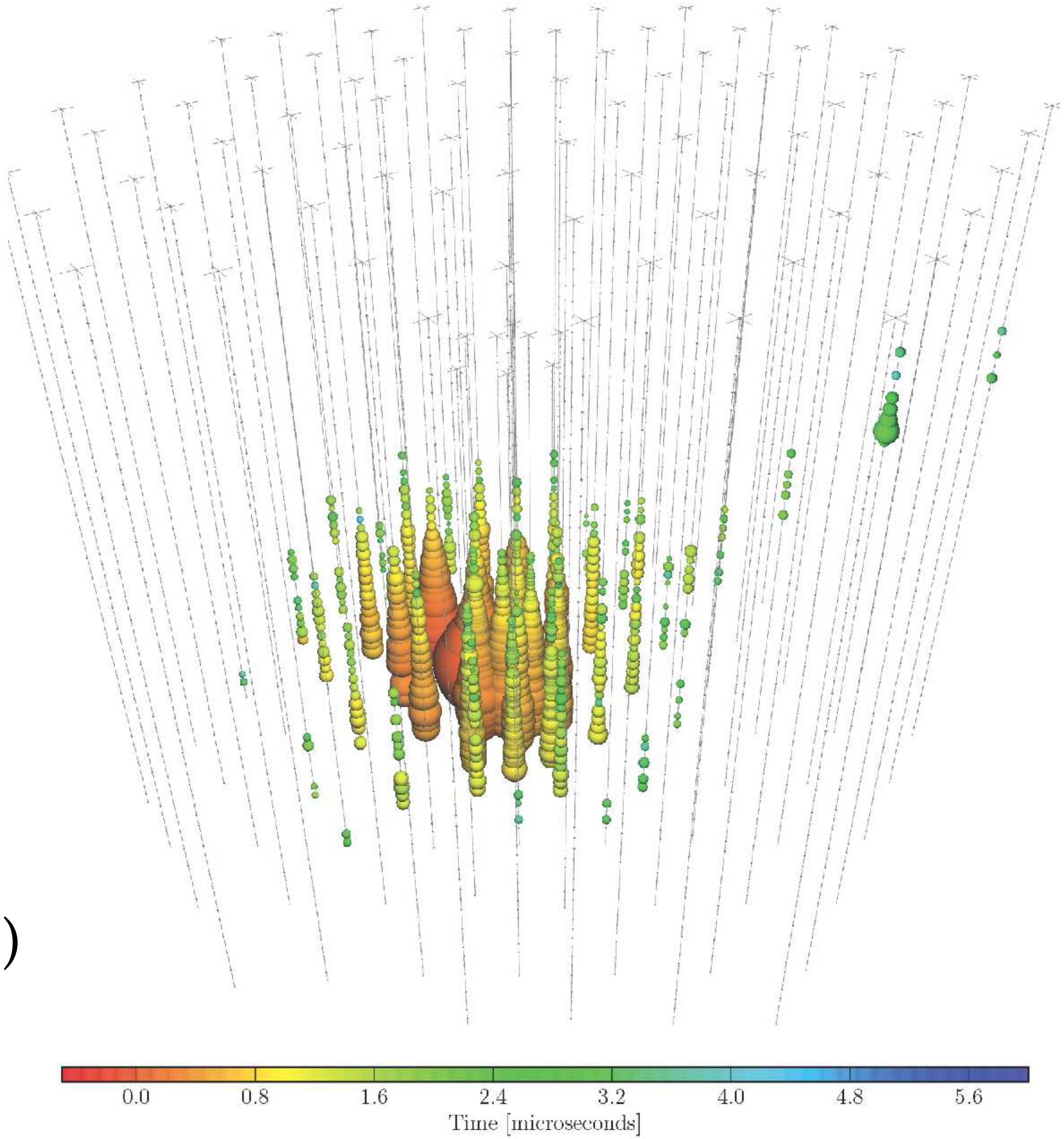
Tracks — From CC ν_μ mainly





Shower
(IceCube event #22)

Track
(IceCube event #15)



What has IceCube found so far (6 years)?

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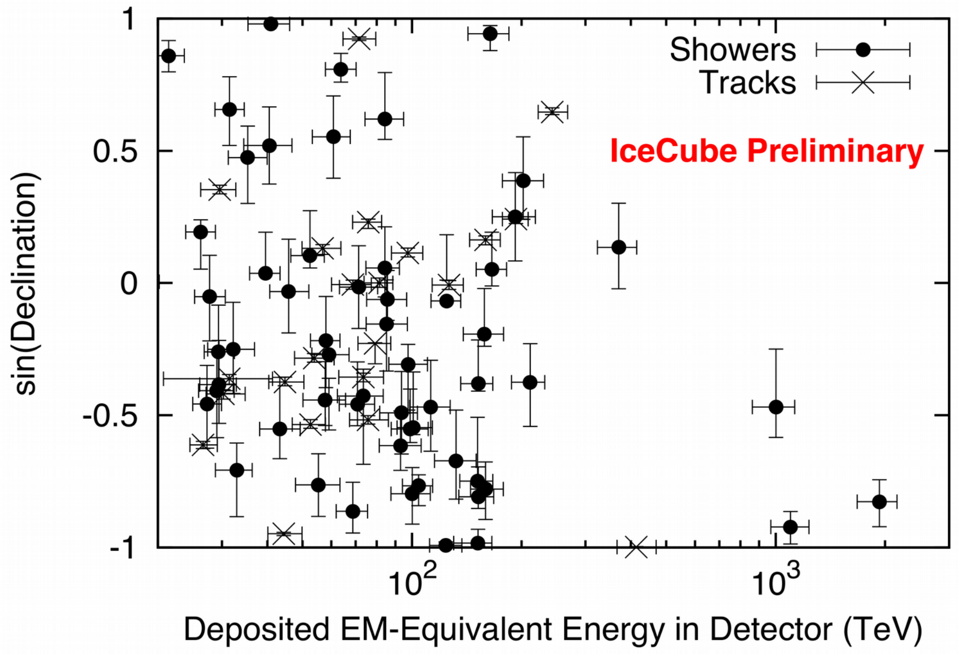
80 contained events between 18 TeV – 2 PeV

(16 atm. neutrinos, 25 atm. muons)



C. Kopper, ICRC 2017

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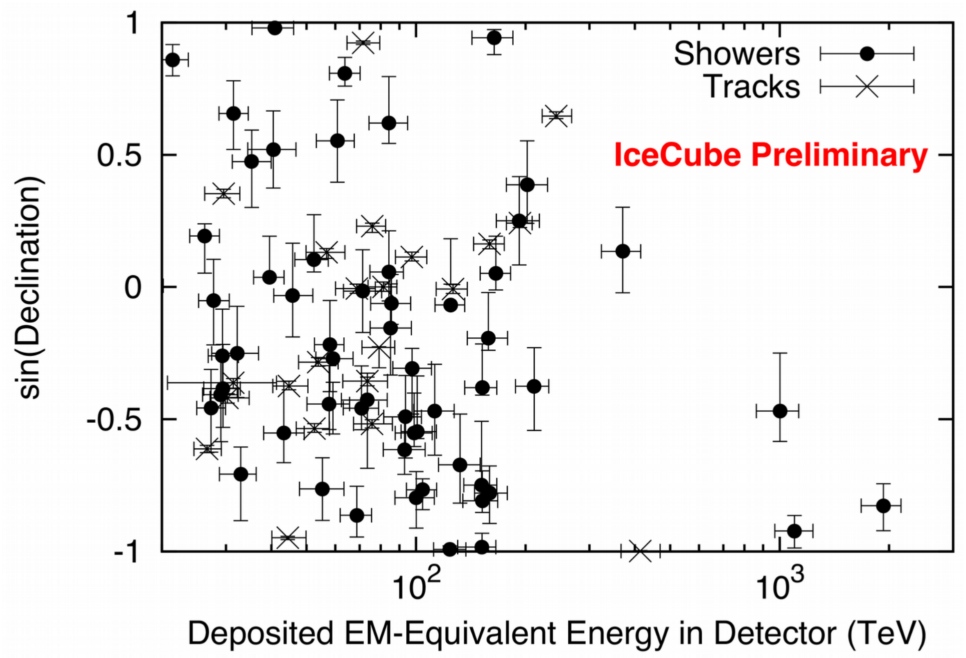
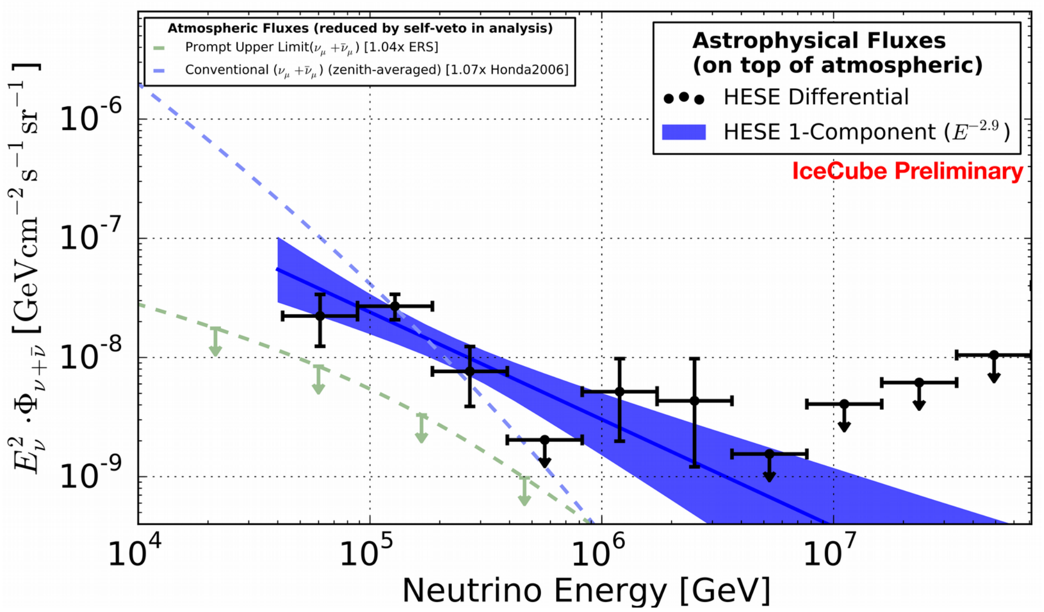


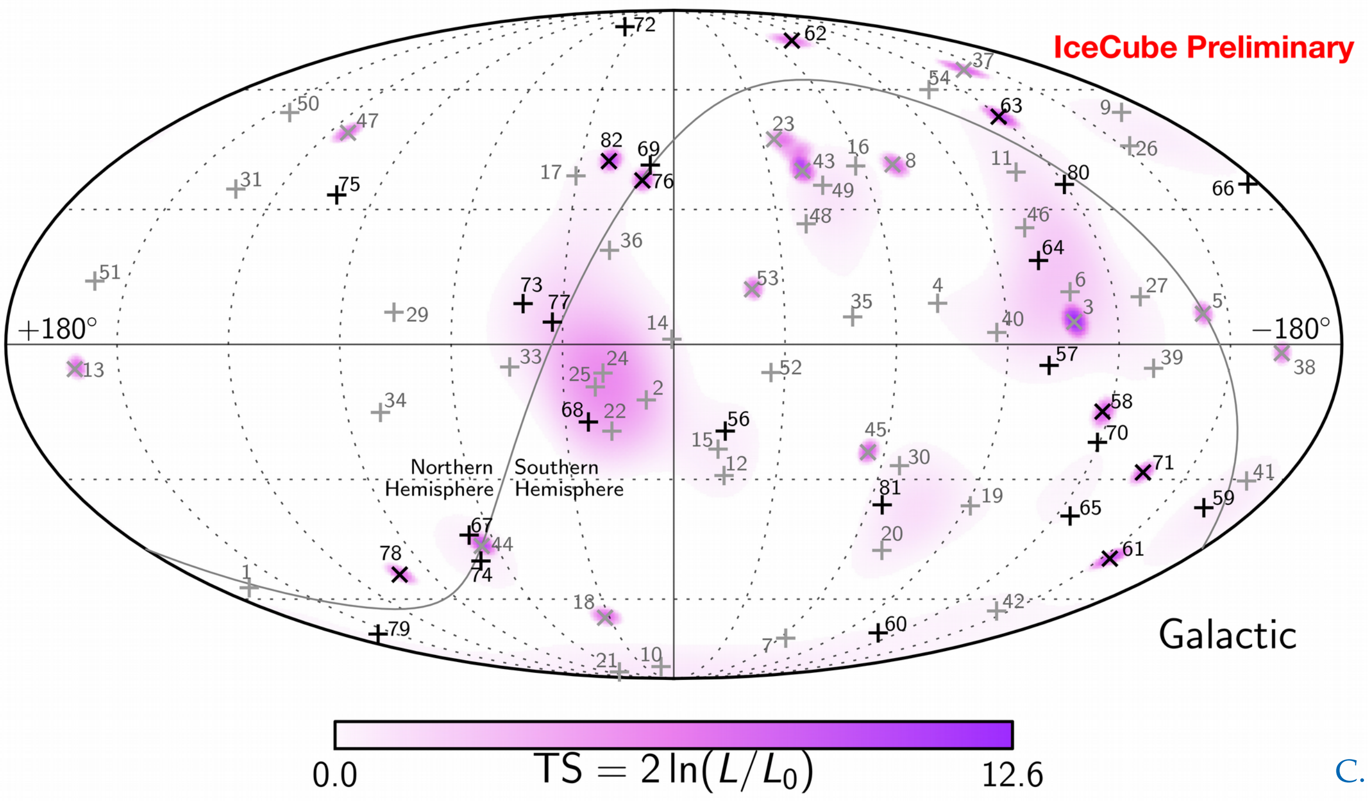
Astrophysical ν flux detected at > 7σ
(Normalization ok, but steep spectrum)



C. Kopper, ICRC 2017

What has IceCube found so far (6 years)?

Arrival directions compatible with isotropy



C. Kopper, ICRC 2017

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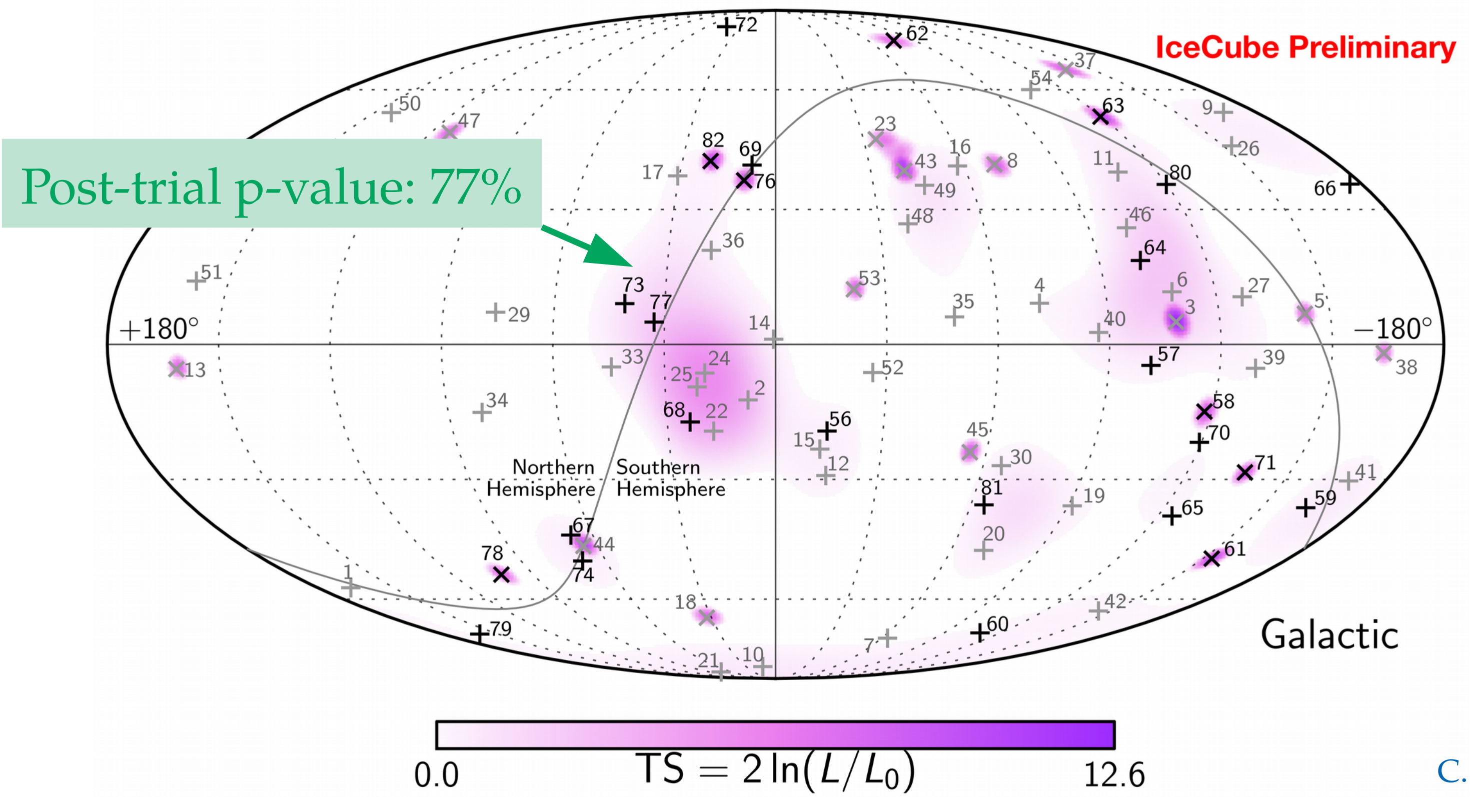
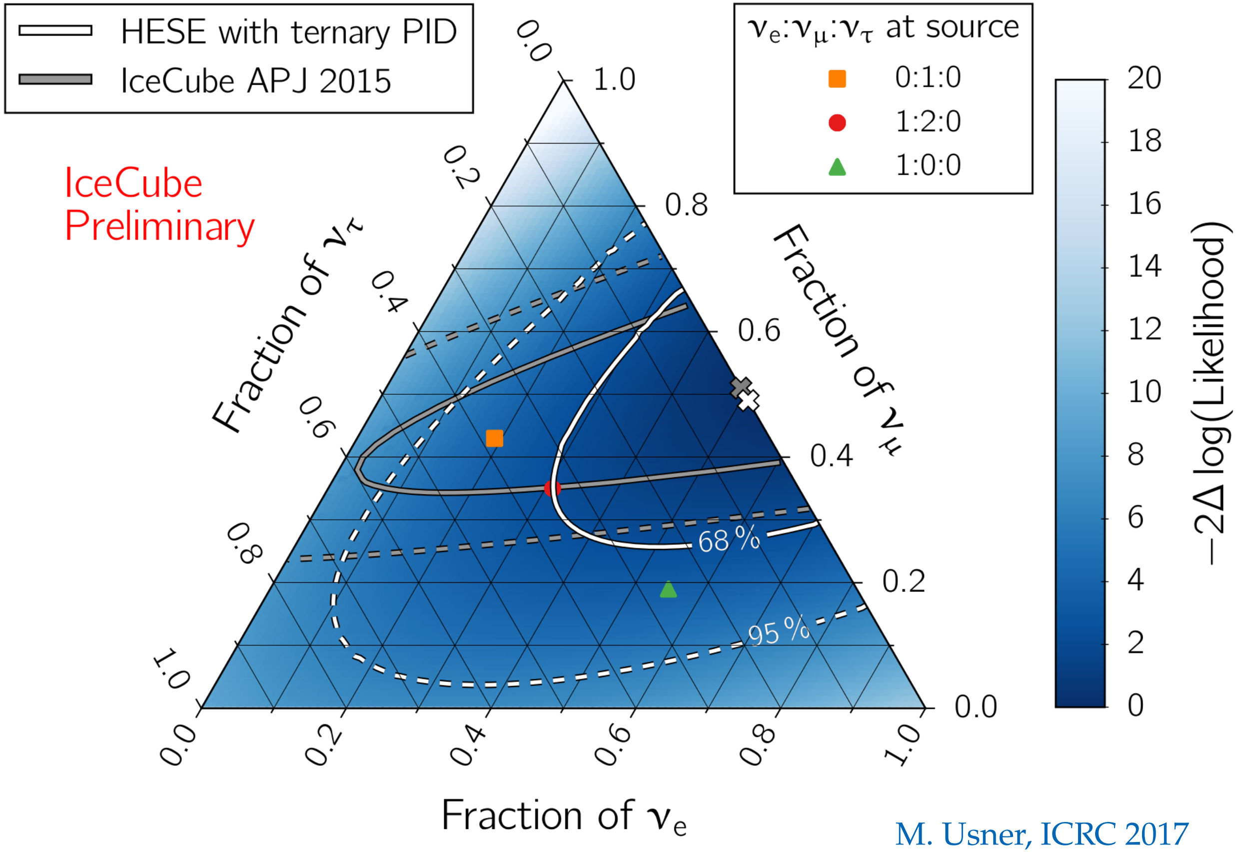


C. Kopper, ICRC 2017

What has IceCube found so far (6 years)?

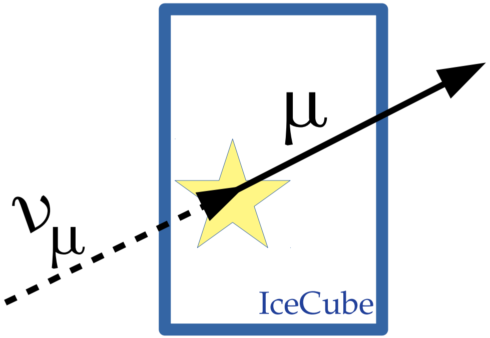
Flavor composition compatible with equal proportion of each flavor



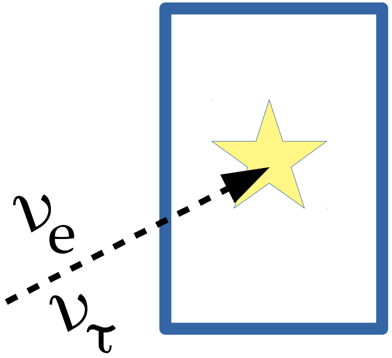
M. Usner, ICRC 2017

Contained vs. uncontained νN interactions

Contained events



Starting track



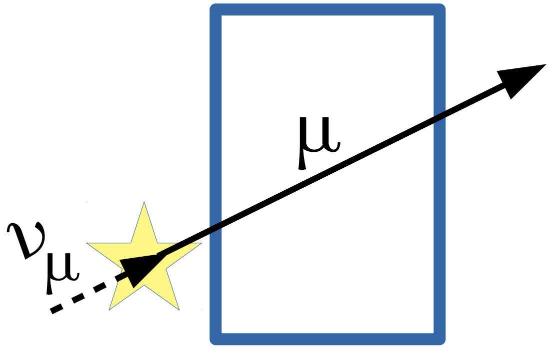
Shower

Pro: Clean determination of E_ν

Con: Few events (<100)

Ref.: MB & A. Connolly, 1711.11043

Uncontained events



Through-going muon

Pro: Lots of events (~10k used)

Con: Uncertain estimates of E_ν

Ref.: IceCube, Nature 2017, 1711.08119

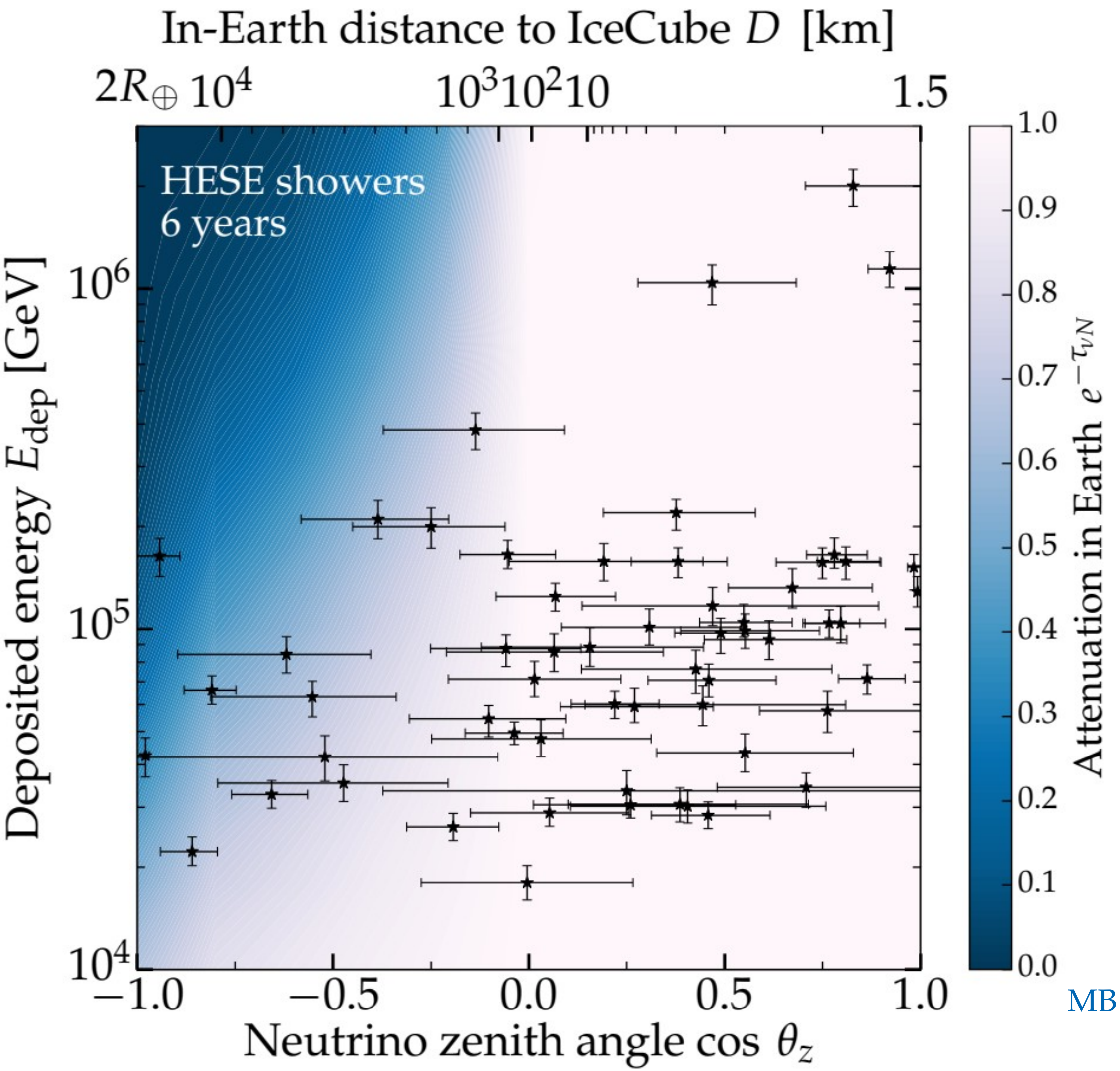
Cross section from contained events

- $\sigma_{\nu N}$ varies with neutrino energy ⇒ use events where E_ν is well-reconstructed

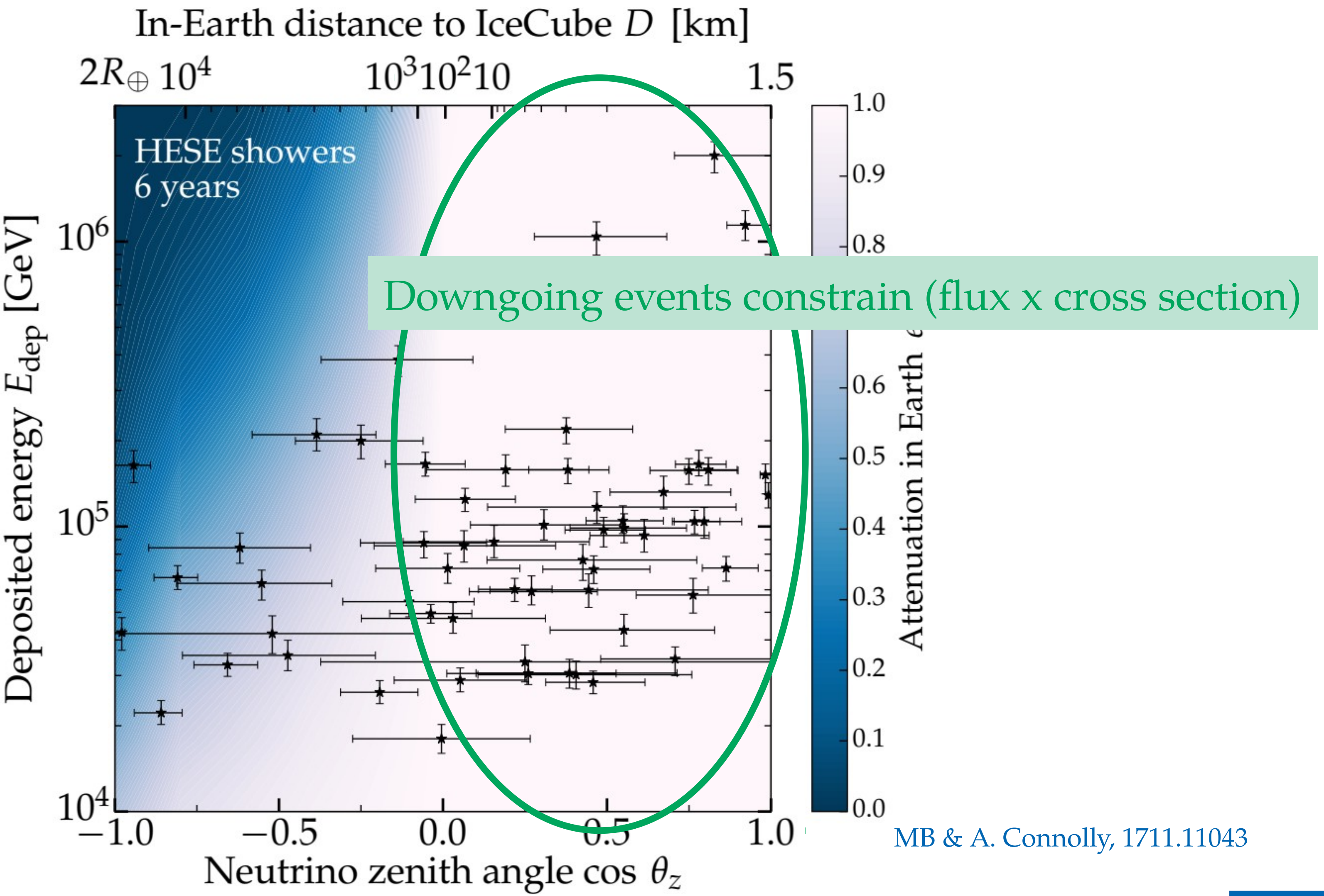
- These are IceCube High-Energy Starting Events (HESE):
  - νN interaction occurs inside the detector
  - ☑ **Showers:** completely contained in the detector ($E_{dep} \approx E_\nu$)
  - ☒ **Tracks:** partially contained ($E_{dep} < E_\nu$)

- We use the 58 publicly available HESE showers (6-year sample)

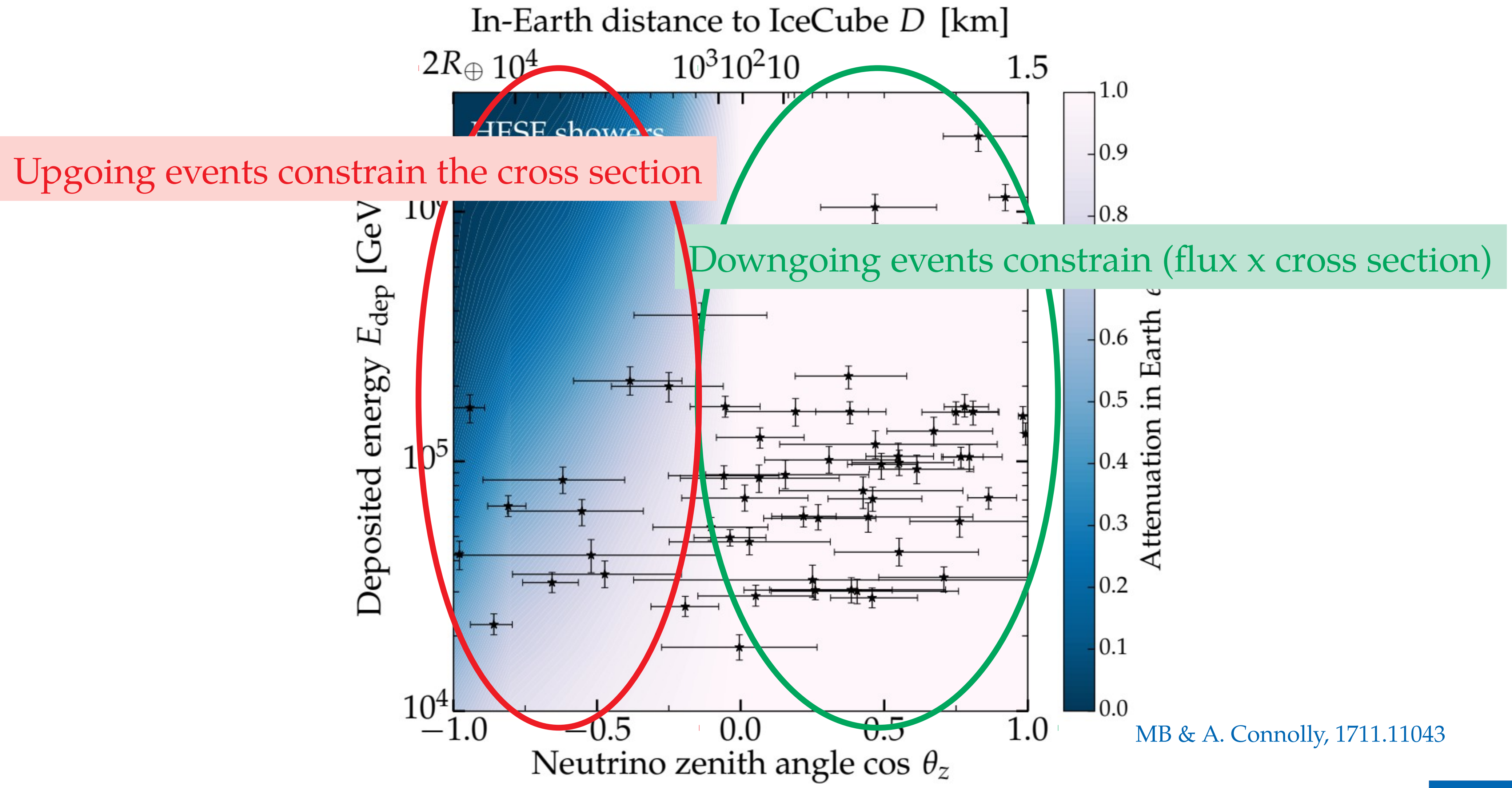
- HESE tracks *could* be used
  – but we would need non-public data to reconstruct E_ν without bias



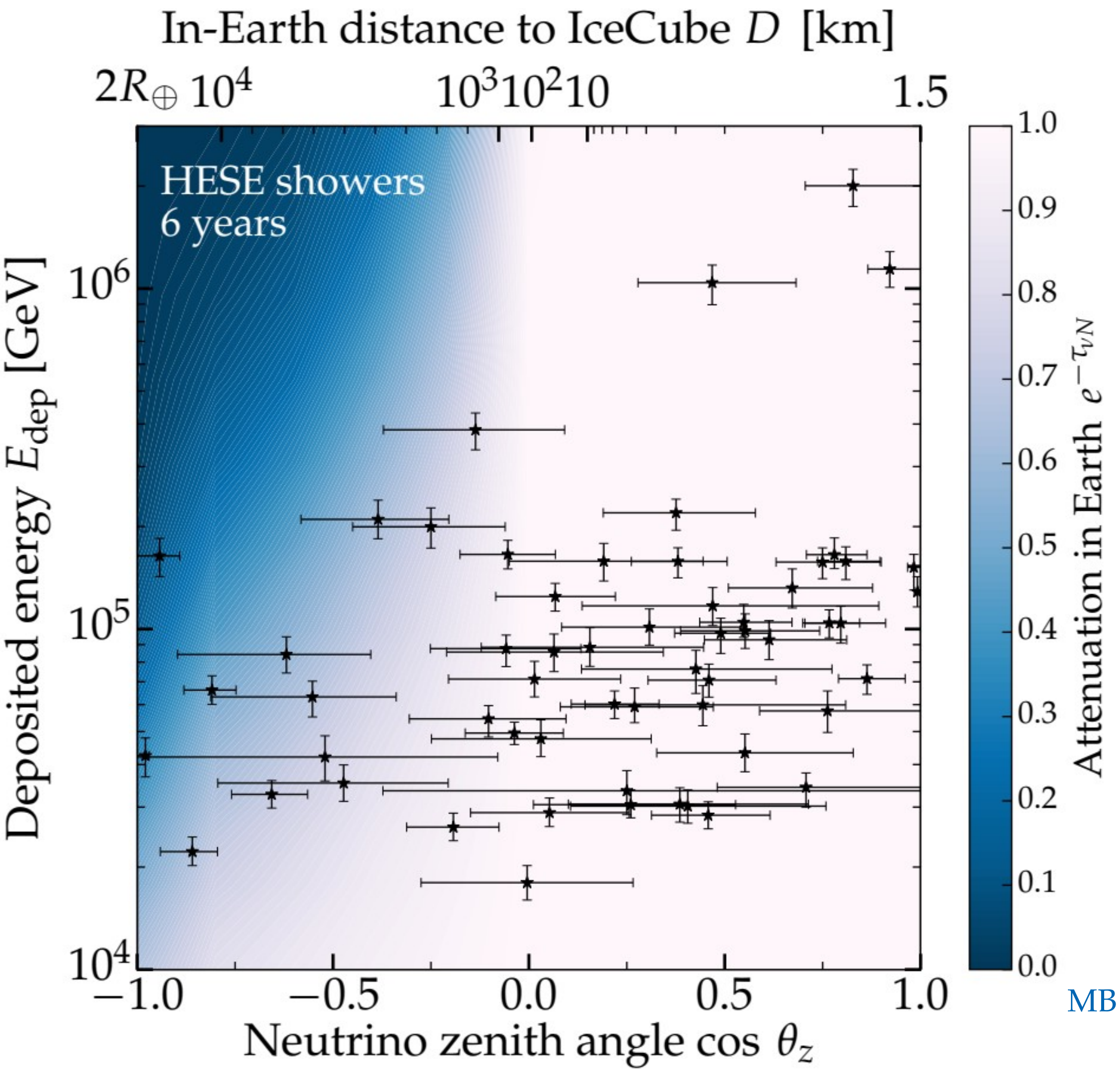
MB & A. Connolly, 1711.11043



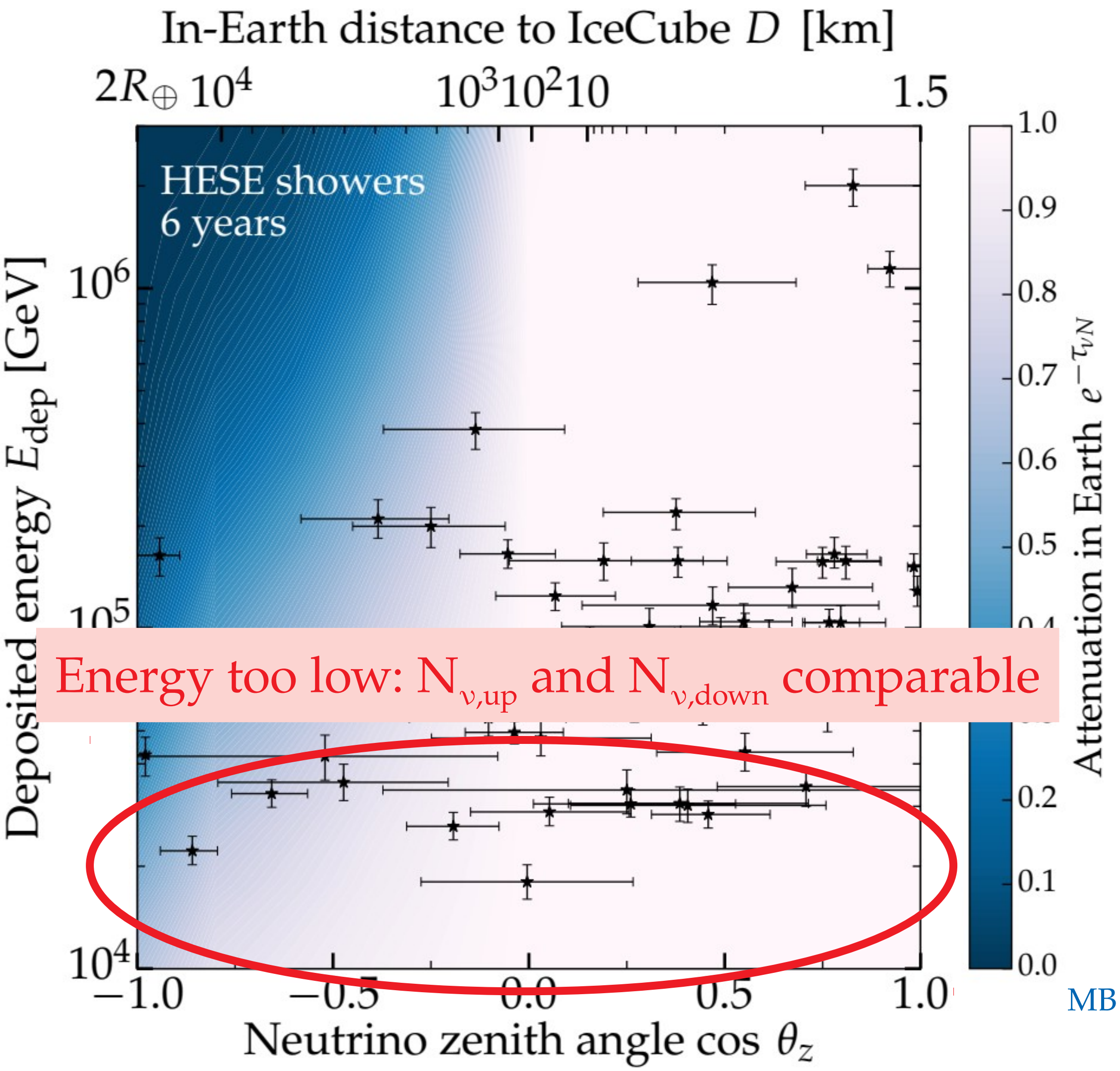
MB & A. Connolly, 1711.11043



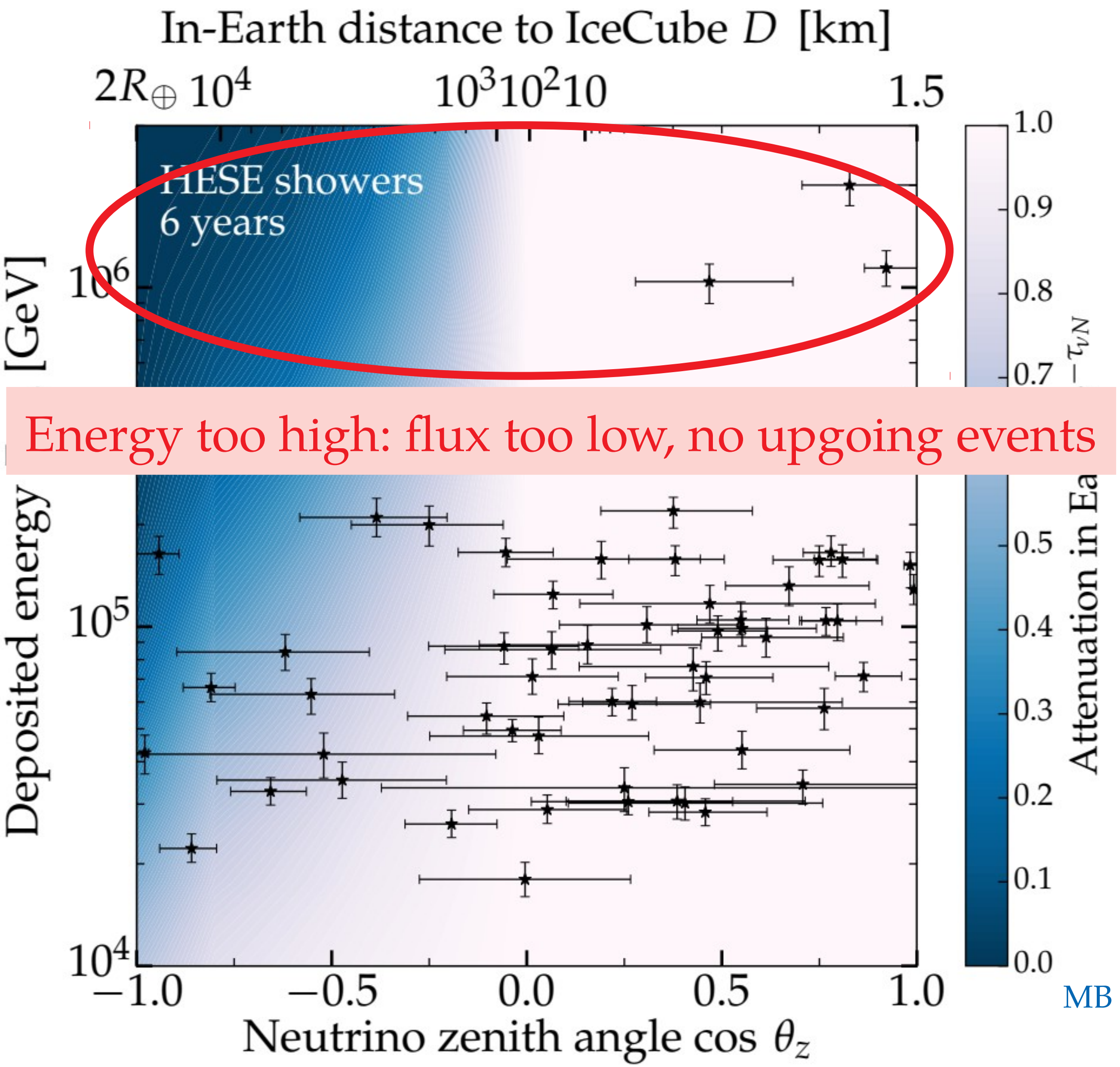
MB & A. Connolly, 1711.11043



MB & A. Connolly, 1711.11043

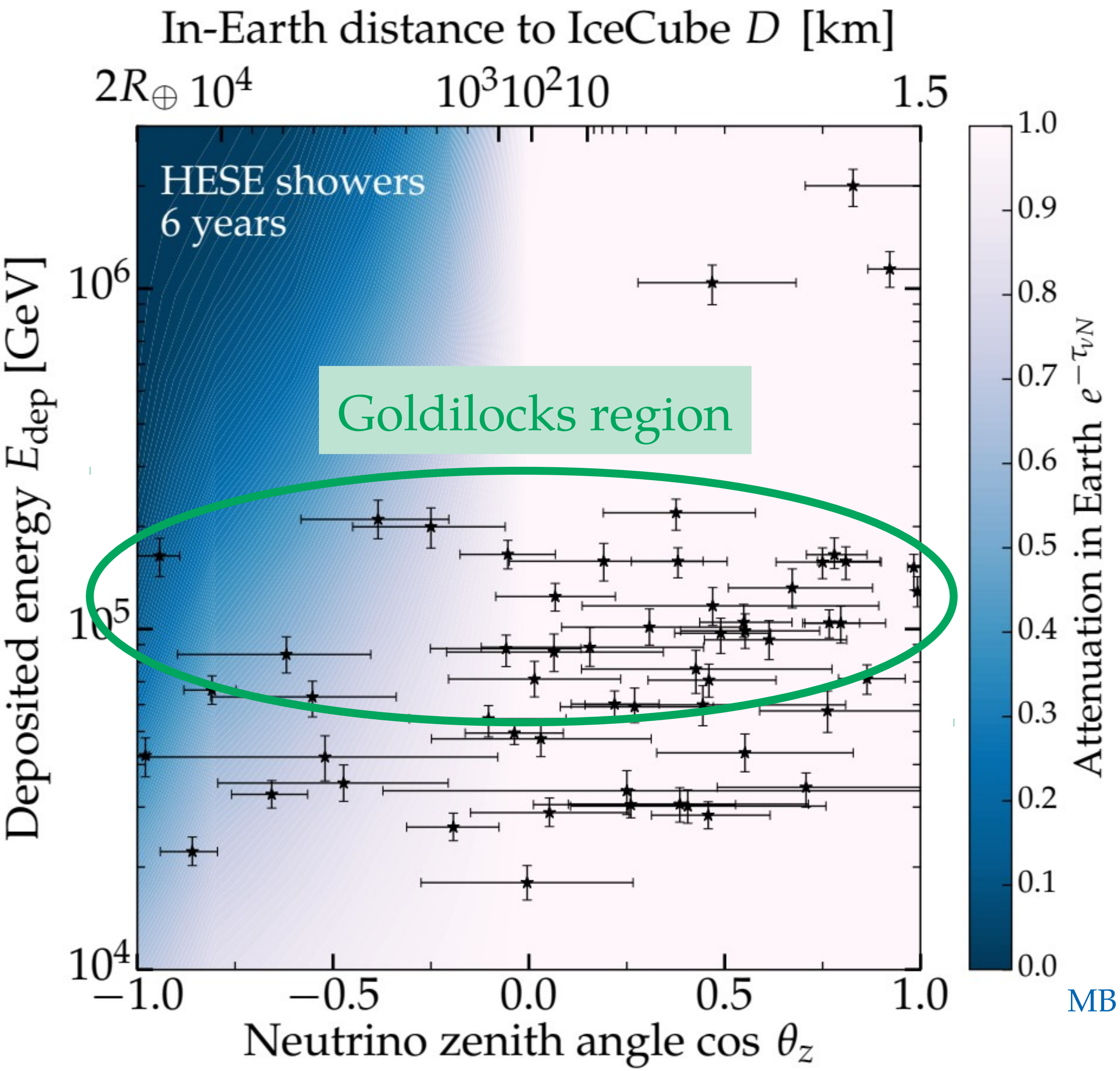


MB & A. Connolly, 1711.11043



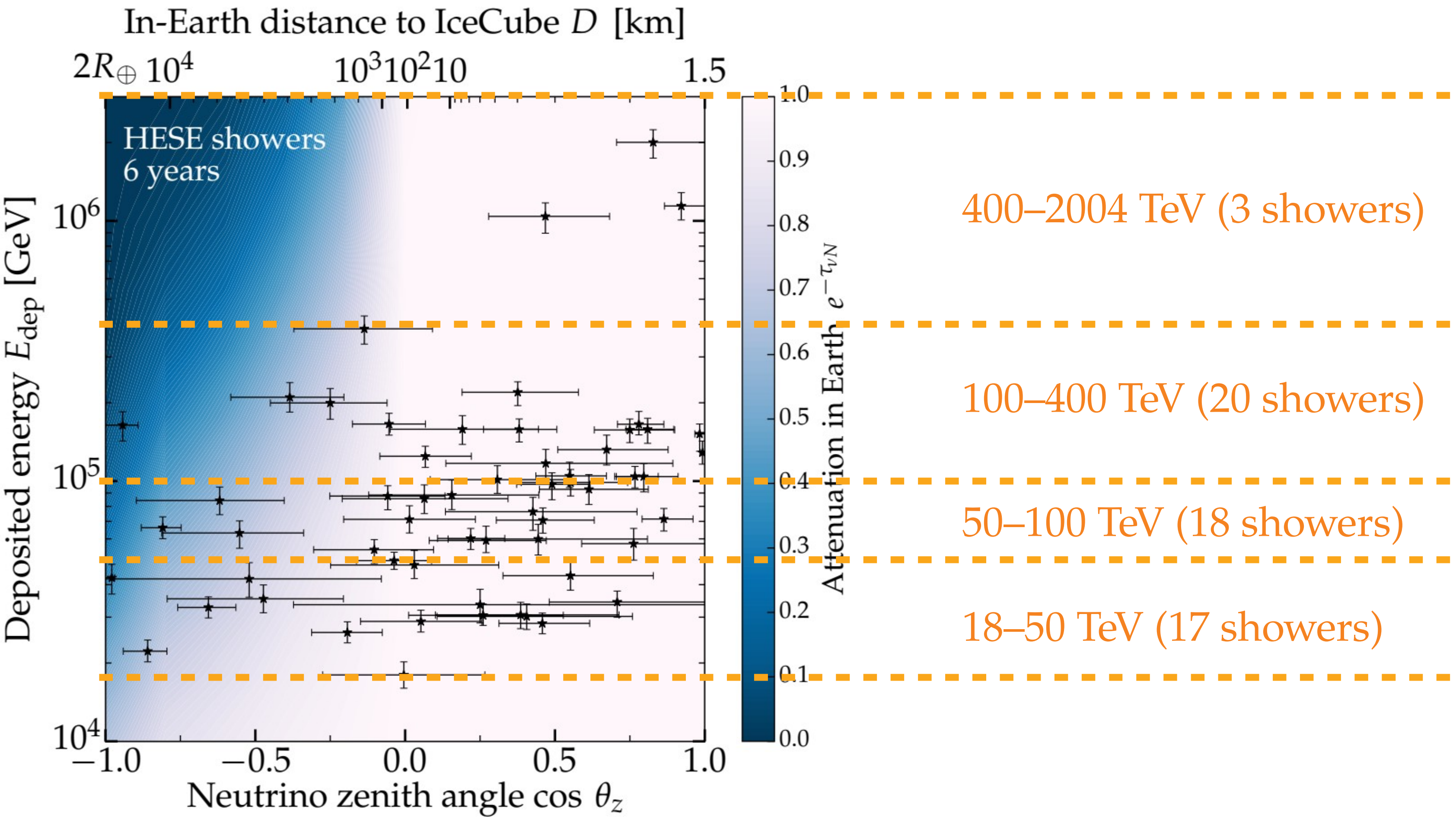
Energy too high: flux too low, no upgoing events

MB & A. Connolly, 1711.11043



MB & A. Connolly, 1711.11043

Bin-by-bin analysis



Sensitivity to σ in each bin

Number of contained events in an energy bin:

$$N_\nu \sim \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-\tau} = \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-L \sigma_{\nu N} n_N}$$

Downgoing (no matter)

$$N_{\nu,\mathrm{dn}} \sim \Phi_\nu \cdot \sigma_{\nu N}$$

Downgoing events fix the product $\Phi_\nu \cdot \sigma_{\nu N}$

Upgoing (lots of matter)

$$N_{\nu,\mathrm{up}} \sim N_{\nu,\mathrm{dn}} \cdot e^{-\tau}$$

Upgoing events measure $\sigma_{\nu N}$ via τ

Reality check:
Few events (per energy bin), so we are statistics-limited

The fine print

- High-energy ν's: astrophysical (isotropic) + atmospheric (**anisotropic**)
  ↦ We take into account the shape of the atmospheric contribution
- The shape of the astrophysical ν **energy spectrum** is still uncertain
  ↦ We take a $E^{-\gamma}$ spectrum in *narrow* energy bins
- **NC showers** are sub-dominant to **CC showers**, but they are indistinguishable
  ↦ Following Standard-Model predictions, we take $\sigma_{NC} = \sigma_{CC}/3$
- IceCube does not **distinguish ν from $\bar{\nu}$**, and their cross-sections are different
  ↦ We assume equal fluxes, expected from production via pp collisions
  ↦ We assume the avg. ratio $\langle\sigma_{\bar{\nu}N}/\sigma_{\nu N}\rangle$ in each bin known, from SM predictions
- The **flavor composition** of astrophysical neutrinos is still uncertain
  ↦ We assume equal flux of each flavor, compatible with theory and observations

What goes into the (likelihood) mix?

- Inside each energy bin, we freely vary
  - N_{ast} (showers from astrophysical neutrinos)
  - N_{atm} (showers from atmospheric neutrinos)
  - γ (astrophysical spectral index)
  - σ_{CC} (neutrino-nucleon charged-current cross section)
- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
- Maximum likelihood yields σ_{CC} (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

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Including detector resolution
(10% in energy, 15° in direction)

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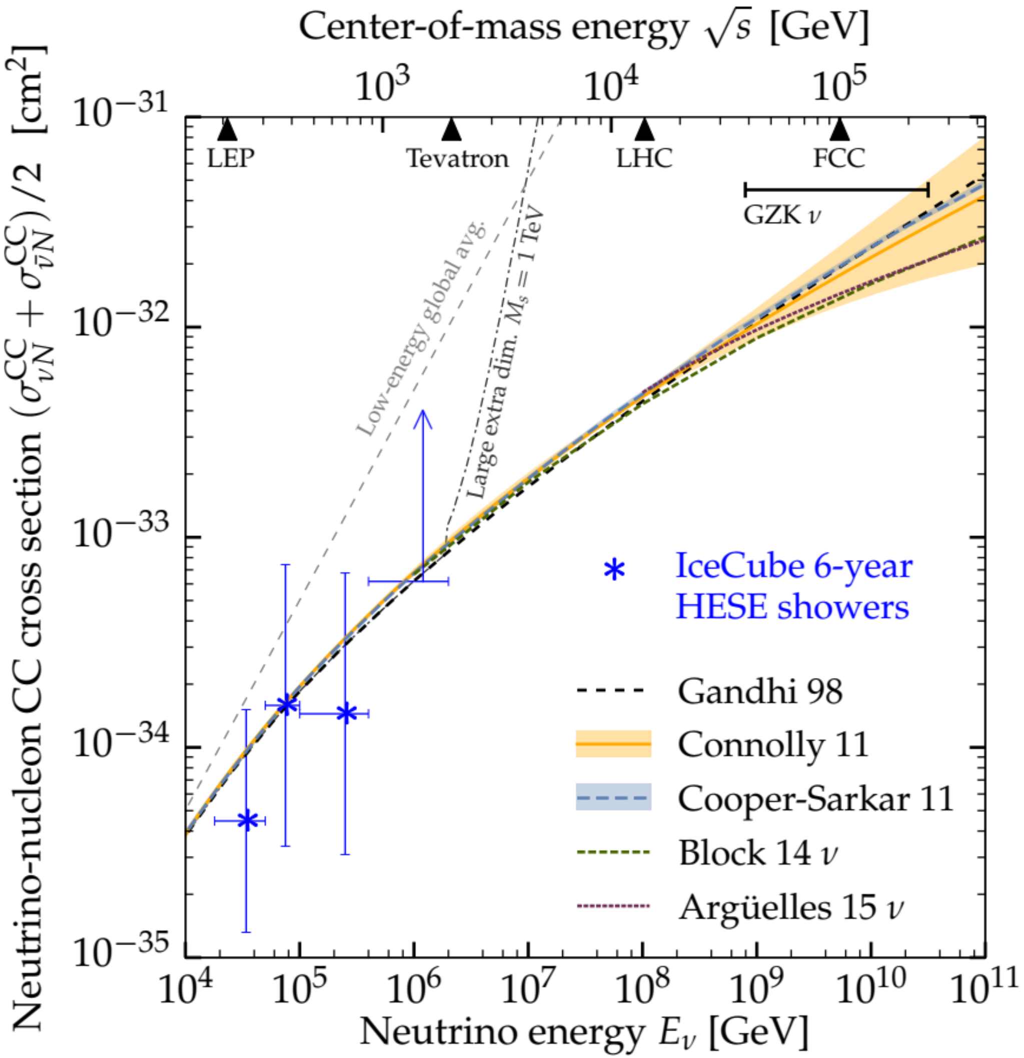
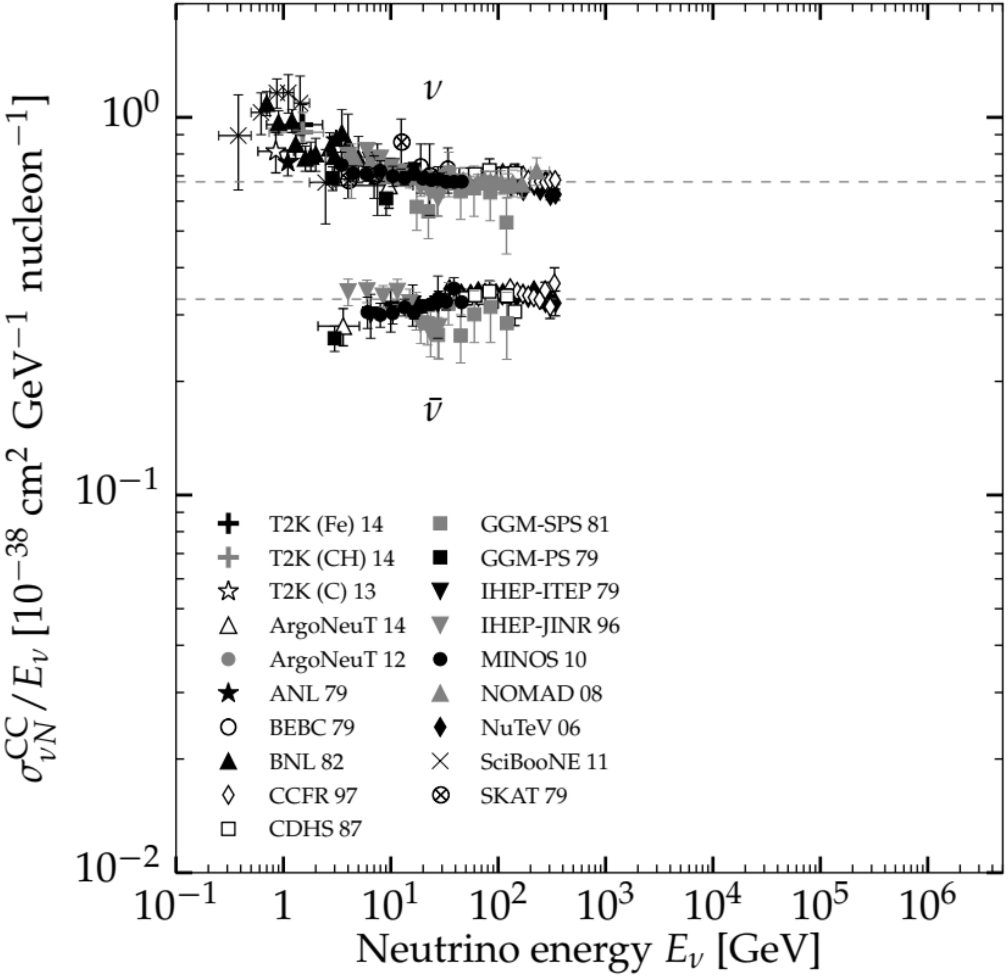
Our result



MB & A. Connolly, 1711.11043

Extending cross section measurements



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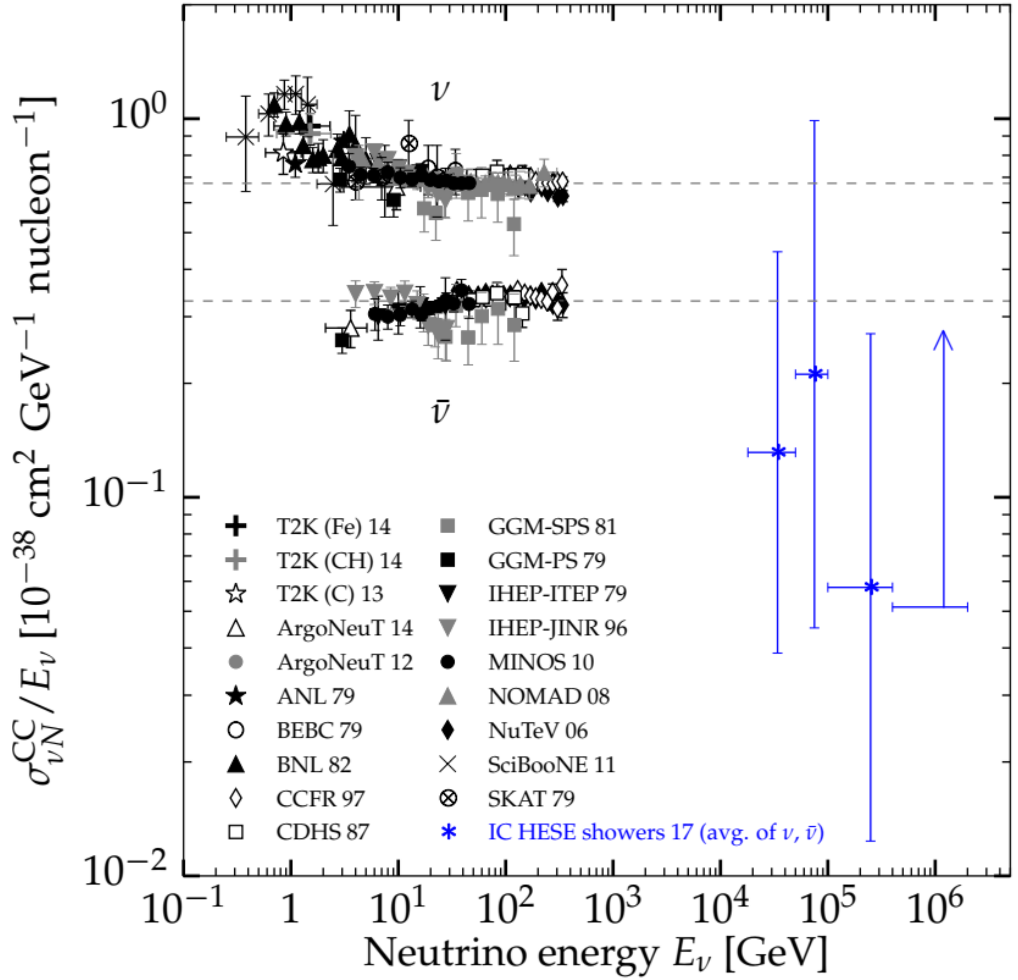
Extending cross section measurements



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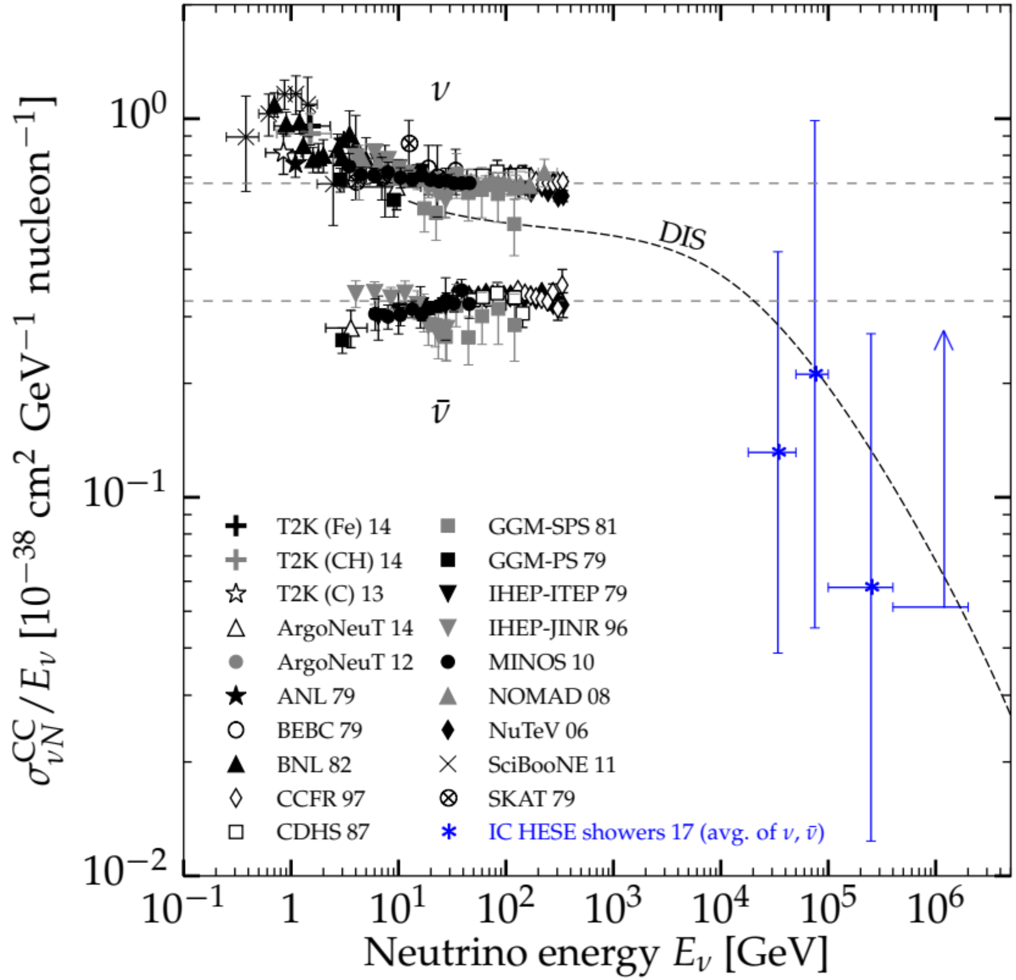


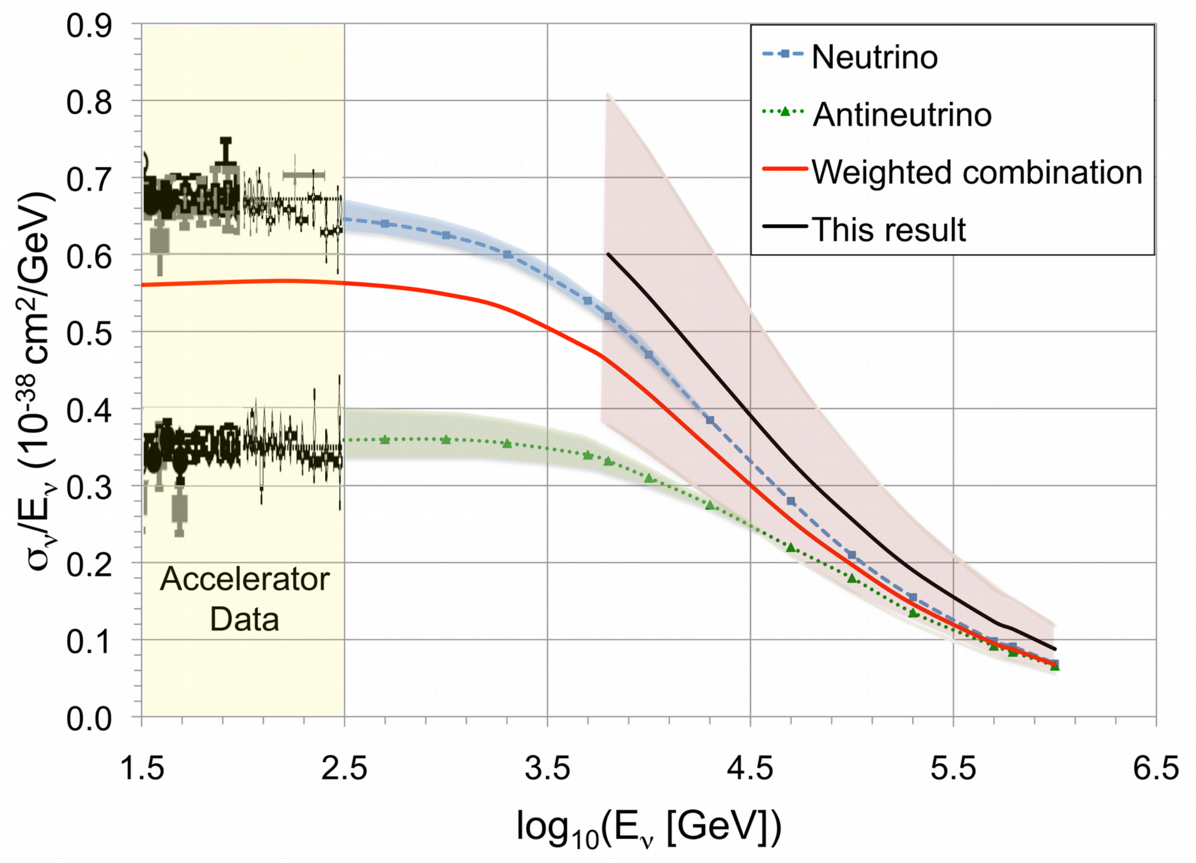
MB & A. Connolly, 1711.11043

How to do better / more?

- Currently, we are statistics-limited
  ↦ Solvable with more data from IceCube, IceCube-Gen2, KM3NeT
- Large errors in arrival direction (~10°) give errors in attenuation
  ↦ Solvable with ongoing IceCube improvements + KM3NeT
- Charged-current + neutral-current cross sections are indistinguishable
  ↦ Solvable (?) with muon and neutron echoes (Li, MB, Beacom 16)
- Cannot separate ν from $\bar{\nu}$
  ↦ Wait to detect Glashow resonance (~6.3 PeV), sensitive only to $\bar{\nu}_e$
- Use starting tracks / through-going muons
  ↦ Doable / done by IceCube (more next)

Using through-going muons instead

- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio $\sigma_{\rm obs}/\sigma_{\rm SM}$
  $1.30^{+0.21}_{-0.19}$ (stat.) $^{+0.39}_{-0.43}$ (syst.)
- All events grouped in a single energy bin 6–980 TeV



IceCube, Nature, 1711.08119

Summary: fundamental physics with astrophysical ν

- We extracted the neutrino-nucleon cross section from 18 TeV to 2 PeV
  ↦ Previously known up to 350 GeV

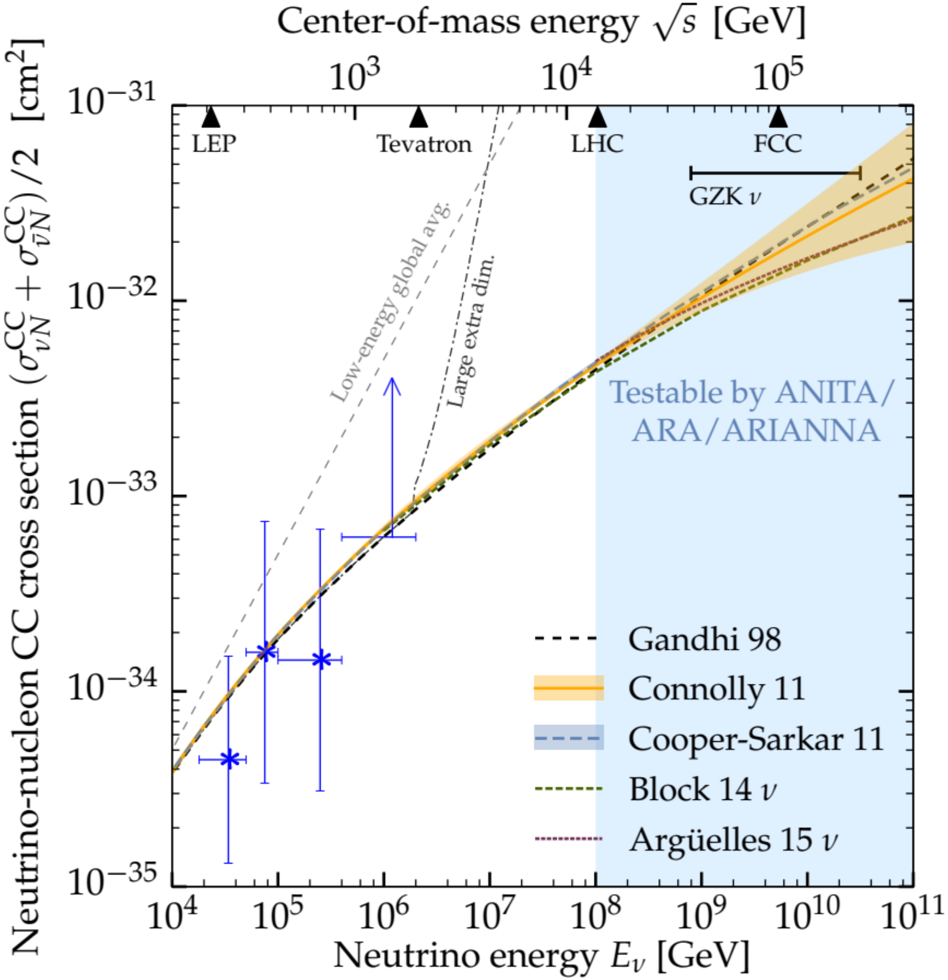
- Found consistency with Standard-Model predictions

- Errors are still large due to statistics and astrophysical unknowns

- But both will be improved in the future

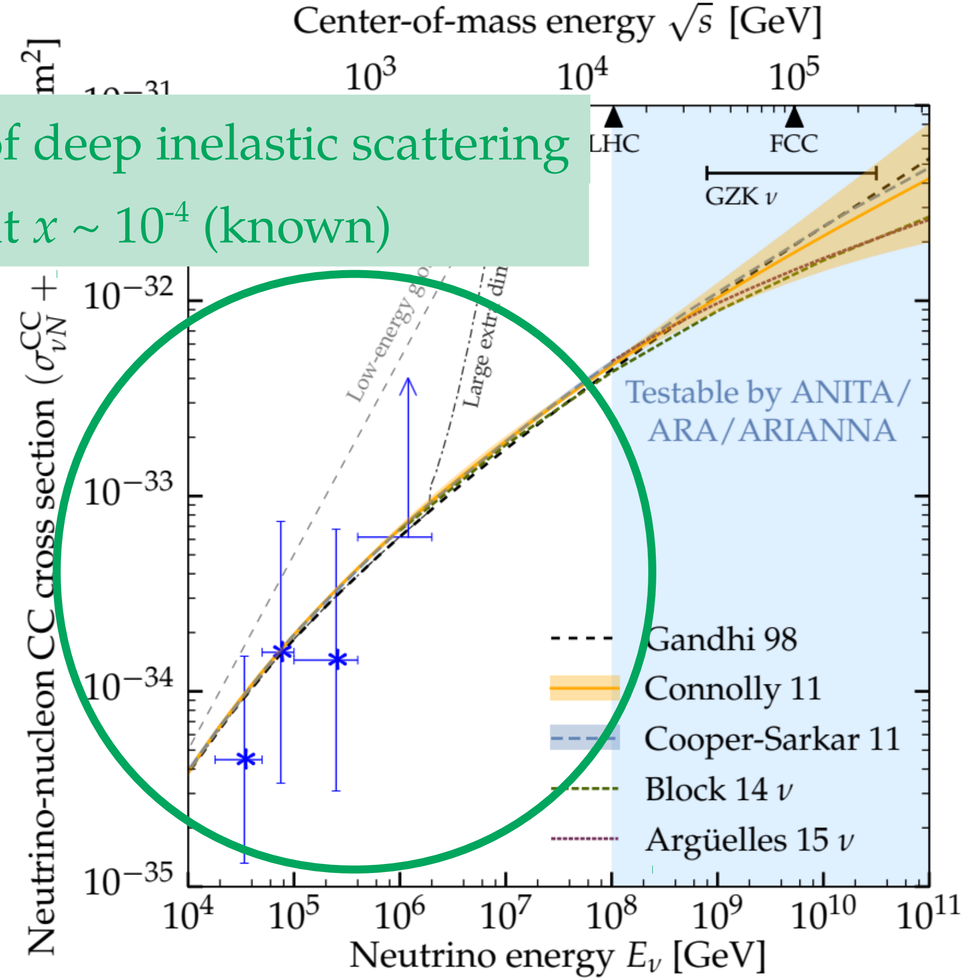
Neutrino telescopes can probe fundamental particle physics
(cross section, flavor composition, anisotropies)

Quo vadis: IceCube vs. ANITA / ARA / ARIANNA

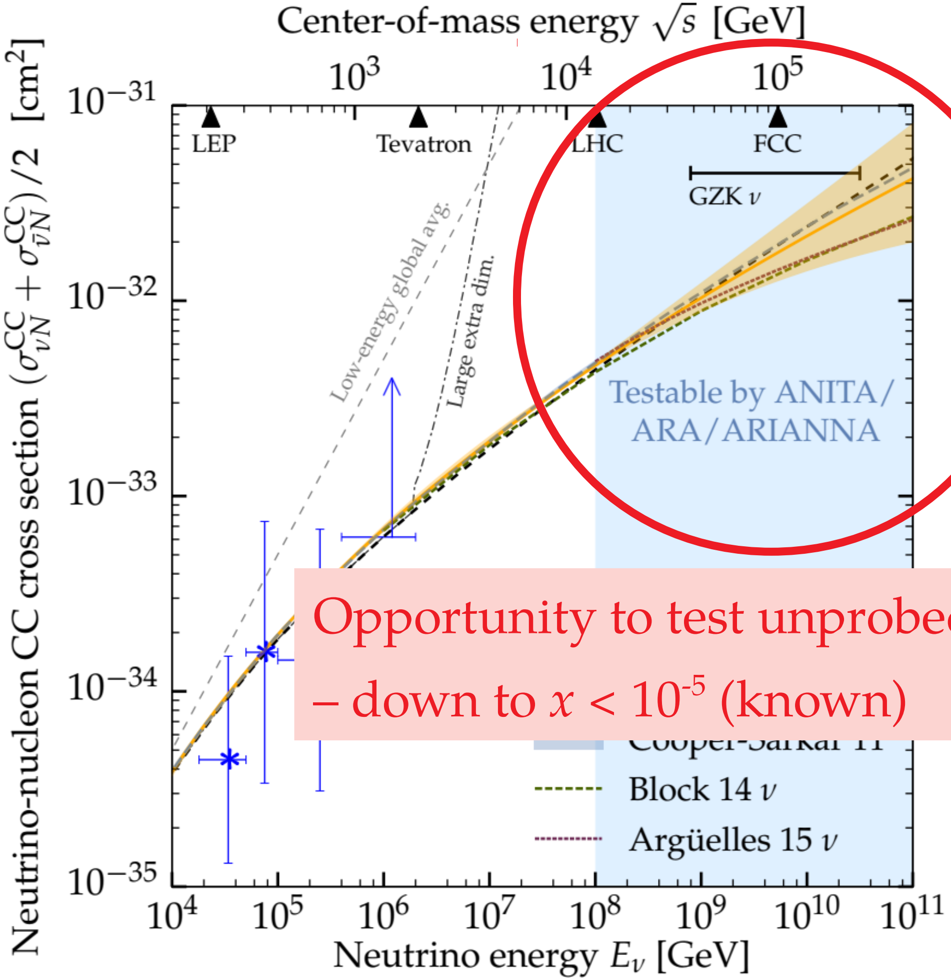


Quo vadis: IceCube vs. ANITA / ARA / ARIANNA

Test predictions of deep inelastic scattering – down to PDFs at $x \sim 10^{-4}$ (known)



Quo vadis: IceCube vs. ANITA/ARA/ARIANNA



Opportunity to test unprobed nucleon structure – down to $x < 10^{-5}$ (known)

Backup slides

Marginalized cross section in each bin

TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle \cdot \sigma_{\nu N}^{\rm CC}$ — where $\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$ is the average ratio of $\bar{\nu}$ to ν cross sections calculated using the standard prediction from Ref. [60] — and $\sigma_{\nu N}^{\rm NC} = \sigma_{\nu N}^{\rm CC}/3$, $\sigma_{\bar{\nu} N}^{\rm NC} = \sigma_{\bar{\nu} N}^{\rm CC}/3$. Uncertainties are statistical plus systematic, added in quadrature.

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{\rm CC} + \sigma_{\bar{\nu} N}^{\rm CC})/{\rm cm}^2]$
18–50	32	0.752	-34.35 ± 0.53
50–100	75	0.825	-33.80 ± 0.67
100–400	250	0.888	-33.84 ± 0.67
400–2004	1202	0.957	> -33.21 (1σ)

MB & A. Connolly, 1711.11043

Neutrino zenith angle distribution

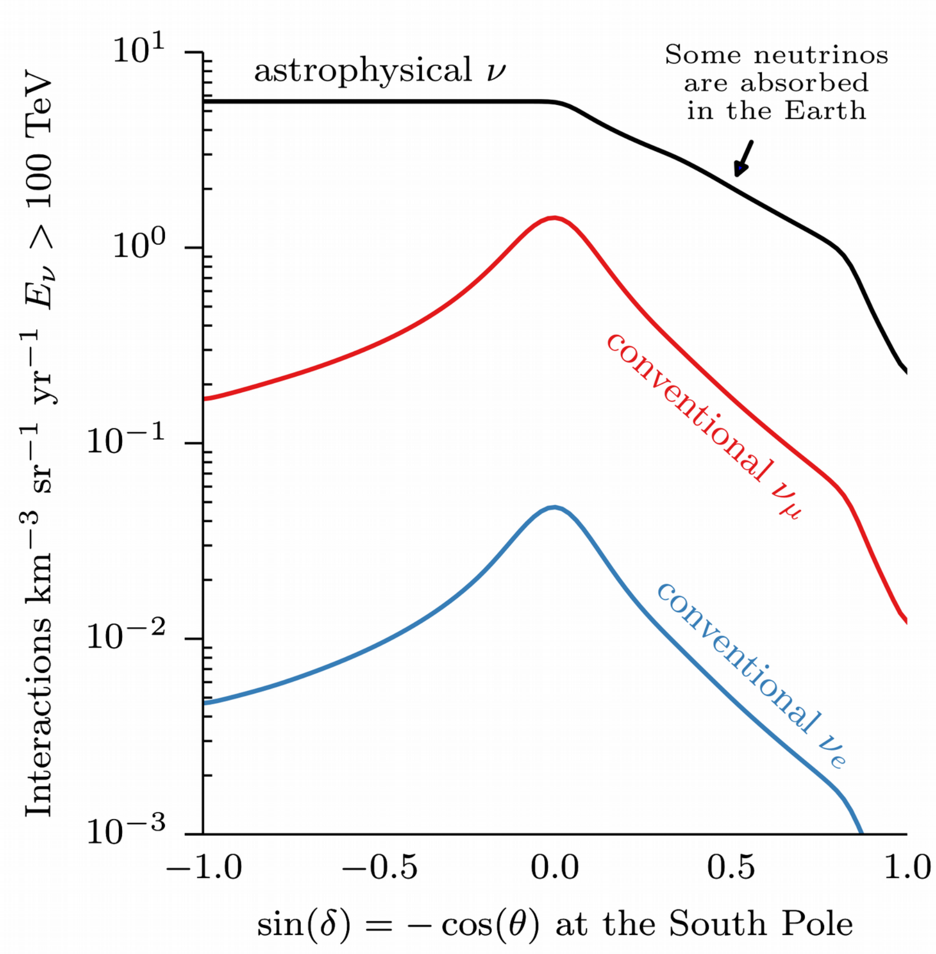


Figure by
Jakob Van Santen
ICRC 2017